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*Operation*

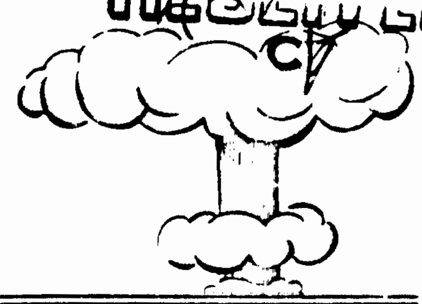
# JANGLE

## NEVADA PROVING GROUNDS
## OCTOBER-NOVEMBER 1951

Project 1(9)-4

BASE SURGE ANALYSIS—HE TESTS





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by

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## PREFACE

The purpose of this report is to present a compilation and analysis of data concerning the behavior of the base surge and related surface phenomena produced by underground explosions in the Dugway Tests in Soils and the Operation JANGLE HE Tests. These two sets of data were combined in order to provide a wide range of charge weight and charge depth and to determine some of the effects of soil properties on surface phenomena.

The formulas and conclusions presented herein were obtained almost entirely from records of TNT charges weighing from 320 to 320,000 lb fired at scaled depths ranging from zero to 3.07 ft/lb$^{1/3}$ in dry clay, dry sand, and wet clay. Extension of the results beyond this range of variables may not be justified.

## ACKNOWLEDGMENTS

The author wishes to acknowledge the cooperation of Mr. H. B. Zackrison of the Protective Construction Branch, Office of the Chief of Engineers, in forwarding prints of the dust cloud photographs and pertinent data for the 1951 Dugway Tests in Soils. Sincere thanks are due to Dr. E. Swift, Jr. for useful comments and suggestions during the program of investigation and the preparation of this report. Mrs. M. L. Milligan's thorough and careful analysis of the material and her valuable comments on the results were extremely helpful in the writing of this report. Mrs. M. M. Lyttle's conscientious preparation of the manuscript is gratefully acknowledged.

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## ABSTRACT

Base surge and related surface phenomena were measured on photographic records of the 1951 Underground Explosion Tests in Soils at Dugway, Utah and the Operation JANGLE HE Tests. Data concerning groundrise, smoke crown, column, jet, and base surge behavior are presented.

A base surge is produced by TNT explosions at scaled depths ($\lambda_c$) ranging from zero to 3.07 ft/lb$^{1/3}$, the greatest depth in these programs, but is small and tenuous at scaled depths less than 0.2 ft/lb$^{1/3}$. The surge has the highest velocity and greatest extent at a $\lambda_c$ of about 1.0 ft/lb$^{1/3}$.

Base surges were formed in the three Dugway soil types; explosions in dry sand produced the largest, wet clay the smallest surges. Explosions in dry clay were intermediate in effectiveness. Thus, it appears that soils with low seismic velocities have the physical characteristics best suited for the formation of a base surge.

Froude scaling is adequate for reducing the surge radial growth data at scaled depths from about 0.2 to 2.0 ft/lb$^{1/3}$. At a $\lambda_c$ of 0.508 ft/lb$^{1/3}$, comparison with liquid model results indicates a 1.9 ratio of column density to atmospheric density. Similarities between the base surges formed by underwater and underground explosions are noted.

Areas of dust deposit and crater dimensions also indicate that a scaled depth of 1.0 ft/lb$^{1/3}$ is near the optimum for base surge formation.

TNT and Pentolite charges with different volumes but equivalent energy formed similar base surges in a small-scale test.

# CHAPTER 1

## ANALYSIS OF DATA

### 1.1 SOURCES OF DATA

The data presented in this report were obtained from photographic records of the Underground Explosion Tests in Soils at the Dugway Proving Ground, Utah[1] in 1951 and the series of underground high explosive tests conducted in Nevada in 1951 as part of Operation JANGLE.[2]

Motion picture records of the Dugway Dry Clay Tests were obtained for the Naval Ordnance Laboratory by Charles H. Bradley, Jr. Timing marks (100 per second) were placed on the margin of 35 mm film by an electronic timer, and a length scale was established from markers placed a known distance apart at the location of the charge or by the use of the lens focal length and the distance from the camera to the explosion. Measurements were made from continuous prints of the 35 mm film, enlarged 5 times. A 16 mm kodachrome record without timing was obtained.

Prints of the dust cloud photographs of the Dry Clay, Dry Sand, and Wet Clay Tests at Dugway were provided by the Protective Construction Branch of the Office of the Chief of Engineers, Washington, D. C. This photographic work was carried out by the Institute of Industrial Research of the University of Denver, by subcontract to Engineering Research Associates, Inc.[3] The dust cloud was photographed with still cameras from two positions with an initial angle of 90° between the respective camera lines-of-sight. A clock reading in minutes and seconds was included in the field of view of each camera and the movement of the dust cloud was followed by the operators. Measurements were made from the prints, using the focal length of the camera lens and the distance from the camera to the charge to establish a scale factor.

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[1] Underground Explosion Tests, Program "A" - Tests in Soils, Protective Construction Branch, Engineering Division, Office, Chief of Engineers, Nov. 1950, pp 1-9.

[2] D. C. Campbell, LCDR, USN, Tests and Observations on Craters and Base Surges, JANGLE Report 1(9)-3, 1 Nov. 1951.

[3] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 1, Dry Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-290, 1 Aug. 1951, pp 5-2 to 5-4.

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Ground photography of the Nevada HE tests was conducted by the Sandia Corporation with motion picture and still cameras from as many as five camera stations. Timing records were made, and targets in the field of view were used to establish length scales. Photographic analysis was performed by the Sandia Corporation and data sheets and films were forwarded to NOL for additional study and measurement. Aerial photographs of shots HE-2 and HE-3 in the Nevada series were provided by Major Victor Bloecker of the Office of the Director, Effects Tests.

The rounds for which data are available for this report are summarized in Tables 1.1 and 1.2. For comparison of charges of different weights, a scaled depth of burial, $\lambda_c$, is used:

$$\lambda_c = \frac{d}{W^{1/3}} \tag{1.1}$$

where $d$ = depth to center of charge, ft
$W$ = weight of charge, lb (TNT)

It should be noted that the Dugway Tests include shots with $\lambda_c$ ranging from zero to 3.07 ft/lb$^{1/3}$, while the Nevada work was confined to the relatively shallow depths ranging between $\lambda_c$ values of -0.149 and 0.500 ft/lb$^{1/3}$.

The TNT charges fired at Utah and Nevada consisted of cast blocks of various sizes, stacked to approximate spheres in shape. The pentolite charges used at Nevada were spherical. The vertical dimensions are important for the scaling of depth and are listed in Table 1.3.

## 1.2 MEASUREMENT OF RECORDS

Wherever possible, measurements were made of overall height of the dust cloud, column height and diameter, and base surge height and radius as functions of time. This was done by the Sandia Corporation for the Nevada high explosive tests and by NOL for the Dugway tests. The Sandia analyses were checked for consistency with NOL methods of measurement.

On the longer Dugway records a scale correction for cloud motion toward or away from the camera was computed by using the mean low-level wind velocity for the period during which photographs were obtained.

The initial surface breakthrough of explosion gases from an underground charge is extremely rapid, and high-speed photography is required for its analysis, but the subsequent formation and expansion of the dirt column can usually be resolved with a camera speed of 24 frames per second. Since the base surge does not appear until a few seconds after detonation,

TABLE 1.1

Underground Explosion Tests in Soils
Dugway, Utah, 1951

| Round | Date | Soil Type | Charge Weight W (lb TNT) | Charge Depth d (ft) | Scaled Depth $\lambda_c$ (ft/lb$^{1/3}$) | Records Used: NOL Motion Picture | Records Used: E.R.A. Still Prints |
|---|---|---|---|---|---|---|---|
| 302 | 3/29 | Dry Clay | 320 | 0 | 0 | x | x |
| 303 | 4/2 | Dry Clay | 320 | 1.3 | 0.190 | x | x |
| 304 | 4/4 | Dry Clay | 320 | 3.5 | 0.512 | x | x |
| 305 | 4/6 | Dry Clay | 320 | 7.0 | 1.02 | x | x |
| 306 | 4/12 | Dry Clay | 320 | 14.0 | 2.05 | x | x |
| 307 | 4/10 | Dry Clay | 320 | 21.0 | 3.07 | x | x |
| 308 | 4/16 | Dry Clay | 2560 | 2.6 | 0.190 | x | x |
| 309 | 4/18 | Dry Clay | 2560 | 7.0 | 0.512 | | x |
| 310 | 4/23 | Dry Clay | 320 | 3.5 | 0.512 | | x |
| 312 | 5/4 | Dry Clay | 2560 | 7.0 | 0.512 | | x |
| 315 | 5/10 | Dry Clay | 40,000 | 17.5 | 0.512 | x | x |
| 318 | 5/22 | Dry Clay | 320,000 | 35.0 | 0.512 | x | x |
| 102 | 6/7 | Dry Sand | 320 | 0 | 0 | | x |
| 103 | 6/7 | Dry Sand | 320 | 1.3 | 0.190 | | x |
| 105 | 6/19 | Dry Sand | 320 | 7.0 | 1.02 | | x |
| 106 | 6/27 | Dry Sand | 320 | 14.0 | 2.05 | | x |
| 108 | 7/10 | Dry Sand | 2560 | 2.6 | 0.190 | | x |
| 110 | 8/13 | Dry Sand | 320 | 3.5 | 0.512 | | x |
| 112 | 7/27 | Dry Sand | 2560 | 7.0 | 0.512 | | x |
| 115 | 8/8 | Dry Sand | 40,000 | 17.5 | 0.512 | | x |
| 402 | 8/23 | Wet Clay | 320 | 2.5 | 0.366 | | x |
| 403 | 8/11 | Wet Clay | 2560 | 5.0 | 0.366 | | x |
| 404 | 8/21 | Wet Clay | 320 | 2.5 | 0.366 | | x |

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TABLE 1.2

Underground Explosion Tests in Nevada
Operation JANGLE, 1951

| Round | Date | Charge Weight W (lb) | Charge Depth d (ft) | Scaled Depth $\lambda_c$ (ft/$lb^{1/3}$) | Charge Composition |
|---|---|---|---|---|---|
| HE-1 | 8/25 | 2,560 | 2.01 | 0.147 | TNT |
| HE-2 | 9/3 | 40,000 | 4.63 | 0.135 | TNT |
| HE-3 | 9/15 | 2,560 | 6.79 | 0.496 | TNT |
| HE-4 | 9/9 | 2,560 | -2.04 | -0.149 | TNT |
| HE-5 | 9/30 | 2,560 | 4.04 | 0.295 | TNT |
| HE-6 | 10/2 | 2,560 | 3.04 | 0.222 | TNT |
| HE-7 | 10/4 | 2,560 | 2.54 | 0.185 | TNT |
| HE-8a | 10/13 | 216 | 1.08 | 0.181 | TNT |
| HE-8b | 10/13 | 177 | 1.08 | *0.181 | Pentolite |
| HE-9a | 10/14 | 216 | 0.83 | 0.139 | TNT |
| HE-9b | 10/14 | 177 | 0.83 | *0.139 | Pentolite |
| HE-10a | 10/14 | 216 | 3.00 | 0.500 | TNT |
| HE-10b | 10/14 | 177 | 3.00 | *0.500 | Pentolite |

* The 177 lb Pentolite charge is assumed to have the energy equivalent of 216 lb of TNT.

TABLE 1.3

Vertical Dimensions of Charges

| Charge Weight (lb) | Charge Composition | Charge Height (inches) |
|---|---|---|
| 177 | Pentolite | 17.75 |
| 216 | TNT | 20.0 |
| 320 | TNT | 24.5 |
| 2,560 | TNT | 49.0 |
| 40,000 | TNT | 117.0 |
| 320,000 | TNT | 234.0 |

its growth can be measured satisfactorily with a slower rate of exposure.

The NOL cameras at Dugway were operated at 24 frames per second and provided excellent coverage of the column and surge formation but the records did not always extend for a sufficient period to cover the complete cycle of growth and dissipation of the surge cloud.

The ERA dust cloud photographs of the Dugway tests were taken at varying intervals of time, though seldom less than 5 seconds apart. This proved inadequate for studying the formation of columns but permitted the tracking of the surge clouds for a long period, particularly after their growth had become relatively slow. In some cases, hills, trucks, or large trees obstructed the view of the surge cloud and made accurate measurement impossible.

The Sandia cameras were operated at different speeds, but the combination of a 24 frame per second 35 mm motion picture camera and an F-56 aerial camera making one exposure per second provided the most satisfactory coverage for record analysis. Greater camera speeds for base surge studies usually proved wasteful of film.

In general, the manual operation of equipment and the following of the dust cloud by the photographer proved superior to the use of remotely-controlled cameras.

Many times at Dugway and Nevada the passage of the shock wave in air raised a layer of surface dust which obscured much of the formation and development of the base surge. With shallow charges this dust layer was sometimes high enough to obscure the initial formation of the entire surge cloud. In these arid regions, cameras at elevated positions provide better records than those operated at ground level. The aerial photographs made in Nevada showed the surge growth more clearly than any surface camera when surface dust obscuration occurred, and in some cases provided measurements that would have been unobtainable from ground level cameras. Aerial photography is probably the best method of tracking a moving surge cloud and also shows some of the changes taking place in the interior of the column and surge. However, ground markings should be provided to establish a distance scale.

## 1.3 SCATTER OF DATA

Experience in studying the effects of underwater explosions has shown that considerable scatter must be expected in the measurements of surface phenomena. It is usually necessary to fire a large number of charges and treat all results statistically in order to obtain consistent relationships between the important variables. For example: the records of a series of 18 one hundred pound charges fired on a river bottom at a 30

inch depth show coefficients of variation of 10.8% for maximum column diameter, 30.3% for maximum surge radius, and 21.6% for maximum surge height.[4] Sufficient data are not available to determine in like manner the degree of dispersion of the data from underground explosions, but charges fired under seemingly identical conditions have produced dissimilar results.

Some of the factors responsible for the scatter of data points are the following:

### 1.3.1 Non-homogeneity of Soil

The soil surrounding a buried charge is almost never homogeneous. Layers of different types of soil and gravel and variations of moisture content with depth all affect the total result. Excavating and filling operations probably affect the density and moisture content of the soil close to the charge. Day-to-day variations in moisture content will also occur during rainy periods. This variation in soil properties is probably responsible in part for the lack of symmetry of the dust clouds produced by most of the explosions studied. In many cases radial throwout and base surge development is pronounced on one side of the charge and relatively minor on the other. Unless camera coverage is extensive or aerial photography is available the true shape of the surge cloud is difficult to determine.

### 1.3.2 Turbulence

The base surge flow is never smooth in appearance. The cloud is in a continual turbulent state, with tongues of material flowing outward at speeds greater than the main cloud mass. Both horizontal and vertical turbulent motion are present and the surge is quite irregular in shape. The erratic motion decreases with time until the dynamic flow has ceased, and measurements of the flow often require considerable smoothing. As the base surge loses its momentum, turbulent atmospheric motion becomes increasingly important and the surge cloud is gradually diluted by the surrounding air. This reduces the sharpness of the outer boundary of the cloud and it becomes tenuous and difficult to see. Objective measurement of the details of the various parts of the jet, column, and base surge become impossible when this diffuse condition is reached.

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[4] A. B. Arons, G. A. Young and M. L. Milligan, Further Investigation of the Base Surge, Interim Report No. 3 of NOL Project 152, NAVORD Report 2144, 1 June 1951, pp 15-18.

### 1.3.3 Accuracy of Measurements

Although every effort is made to obtain accurate time and length scales for the photographic records, minor differences in lens focal lengths, faulty or incomplete timing, and possible errors in measurement of distances may reduce the accuracy of measurements of surface phenomena and contribute to the scatter of the resulting data. In some cases the distance between the cameras and charge is too great for precise measurement of the surface phenomena. The changes in scale due to movement of the entire dust cloud are difficult to estimate because of the generally irregular variation of wind speed and direction. On the shallow charge records, careful study is required to separate the dust produced by the radial throwout and the passage of the shock wave from the true surge cloud.

## 1.4 ANALOGY WITH UNDERWATER EFFECTS

The appearance of the surface phenomena produced by underground explosions is similar to the visible surface effects of underwater explosions and the physical processes of formation are probably somewhat analogous. In this report, the same nomenclature is used for the phenomena produced in soils that was previously applied to the surface phenomena from underwater charges,[5] in order to facilitate comparison of results and to make use of the same scaling procedures in studying the base surge flow.

[5] J. S. Coles and G. A. Young, Investigations of Base Surge Phenomena by Means of High Explosives and a Liquid Model, Interim Report No. 2 of NOL Project 152, NAVORD Report 1744, 1 Sept. 1950.

# CHAPTER 2

## SURFACE PHENOMENA

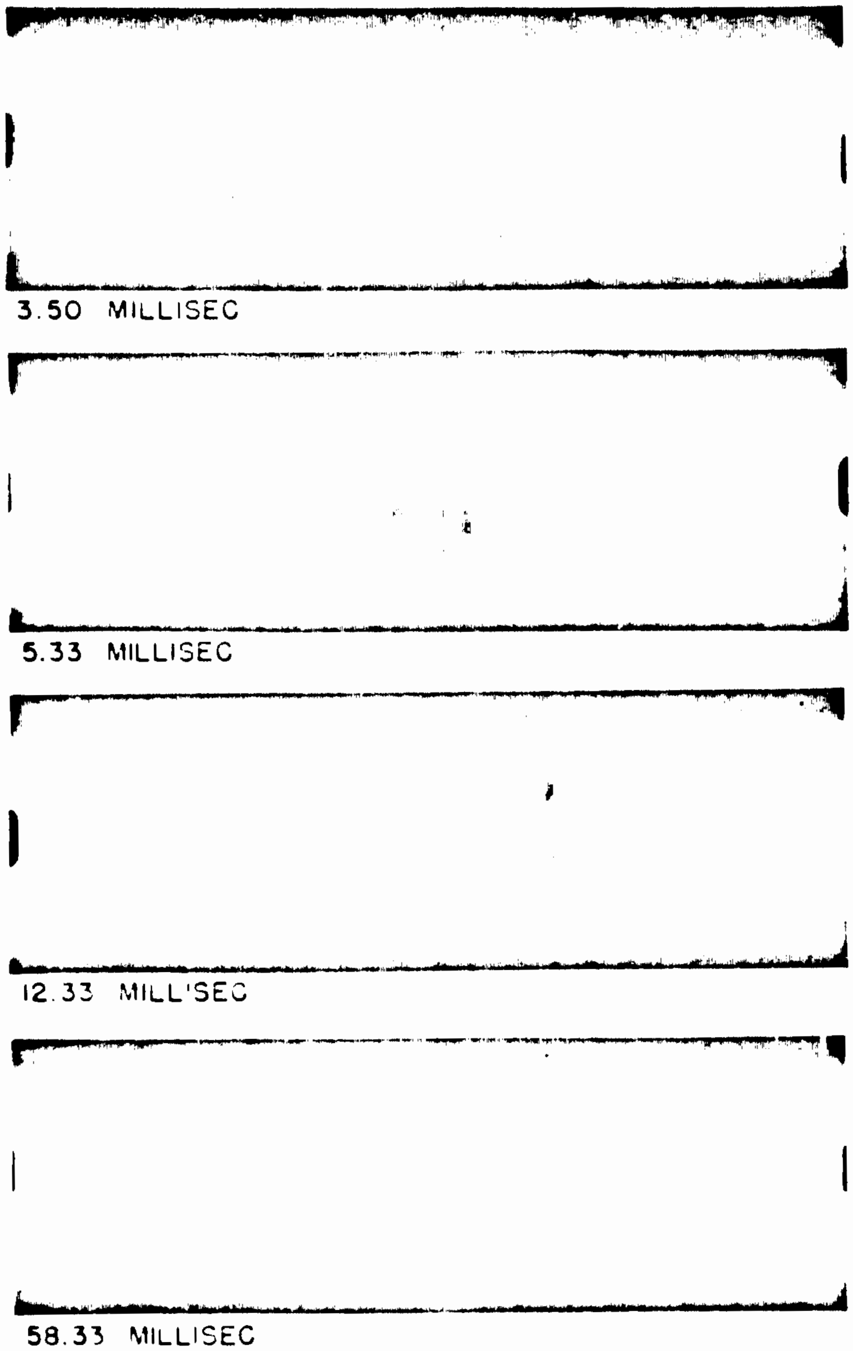
### 2.1 DESCRIPTION AT SCALED DEPTH OF 0.5 FT/LB$^{1/3}$

The appearance and structure of the surface phenomena produced by high explosive charges fired underground are markedly dependent upon charge depth and the character of the soil. As an introduction, it will be useful to describe briefly the sequence of events above the ground level at an intermediate scaled depth ( $\lambda_c$ = 0.5 ft/lb$^{1/3}$ in dry clay) at which all of the important features are relatively large and clearly defined. The 320,000 lb "full scale" charge at Dugway was fired at this scaled depth.

The first visible surface effect is the bulging of the earth above the charge into a smooth dome-shaped mound. Explosion gases start to vent through the upper surface of the elevated ground and the entire earth mound appears to explode into a roughly spherical cloud of smoke and dust, which expands rapidly. The diameter of the earth dome continues to increase, and the ground is lifted to form a cylindrical column, which becomes visible beneath the rising smoke cloud. These features are shown in Figure 2.1, which was obtained from the photographic records of Round HE-3 at Nevada.

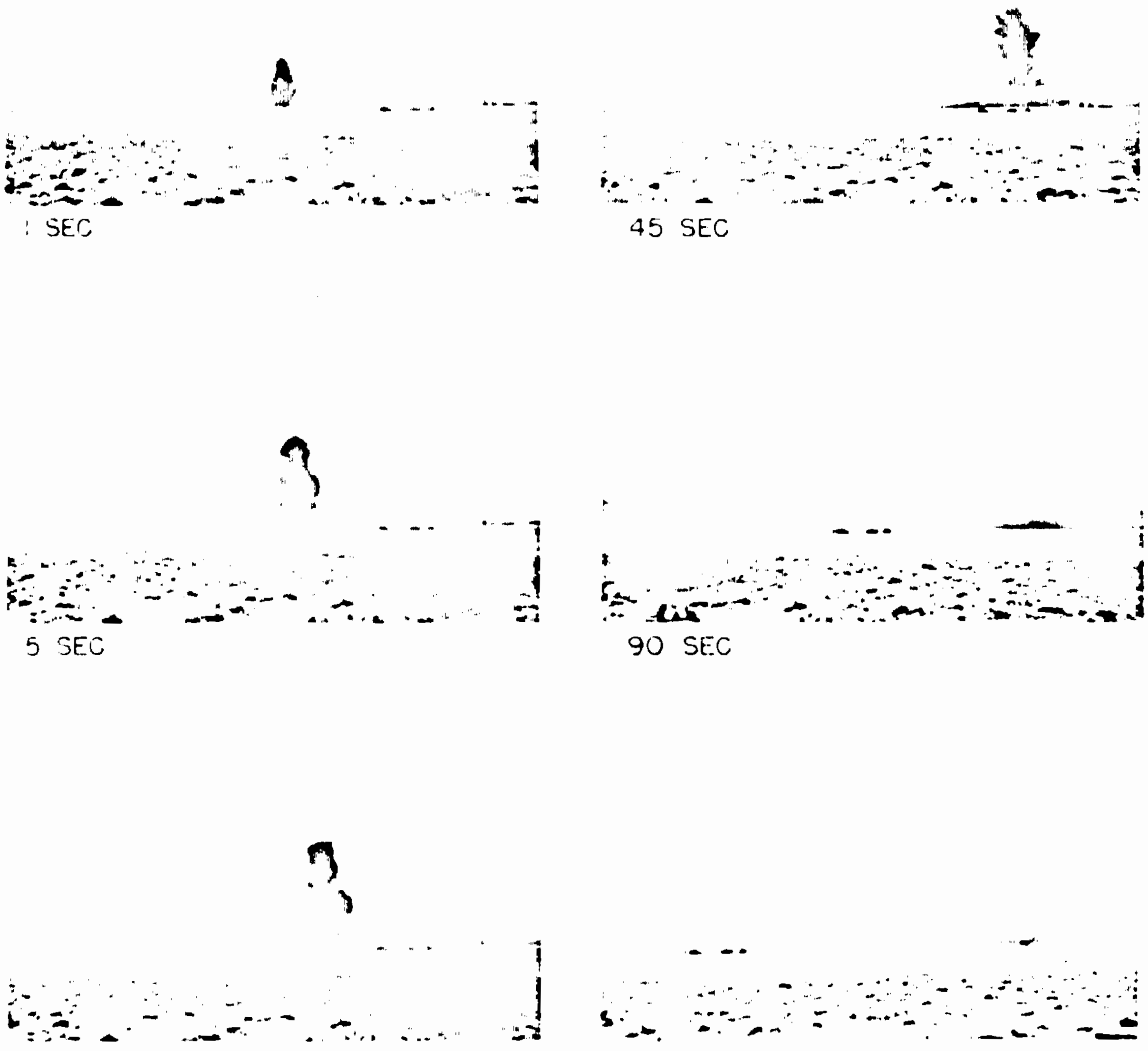
The rounded top of a central jet appears at the center of the expanding smoke cloud and rushes upward at a high velocity, pushing the initially spherical cloud upward and outward into a smoke crown. The jet of explosion gases appears to be rising through the center of the earth column, and contributing to its outward radial expansion. The column then settles and the surge appears at its base while the jet continues to rise and expand. Initially the surge cloud is almost white in appearance and is irregular and turbulent. The smoke crown and jet then fall and flow outward along the ground to contribute additional material to the surge cloud, though, if light winds prevail, some of the upper dust and smoke will remain airborne. Figure 2.2 illustrates this development for Round 304 at Dugway.

The base surge continues to grow in height and diameter, maintaining the shape of a torus, or doughnut, with a shallow central dust layer. The surge cloud moves downwind, its bulk density decreasing due to expansion and mixing with the surrounding air. It gradually rises from the ground and is dispersed by atmospheric turbulence, as shown in the aerial photographs of Round HE-3 in Fig. 2.3.




CHARGE WEIGHT = 2560 LB SCALED DEPTH = 0.496 FT/LB$^{1/3}$
CHARGE DEPTH = 6.79 FT

Fig. 2.1 Rise of Ground and Formation of Smoke Crown and Column
Round HE-3




CHARGE WEIGHT = 320 LB
CHARGE DEPTH = 3.5 FT
SCALED DEPTH = 0.512 FT/LB$^{\frac{1}{3}}$

Fig. 2.2 Formation of Jet and Base Surge - Round 304

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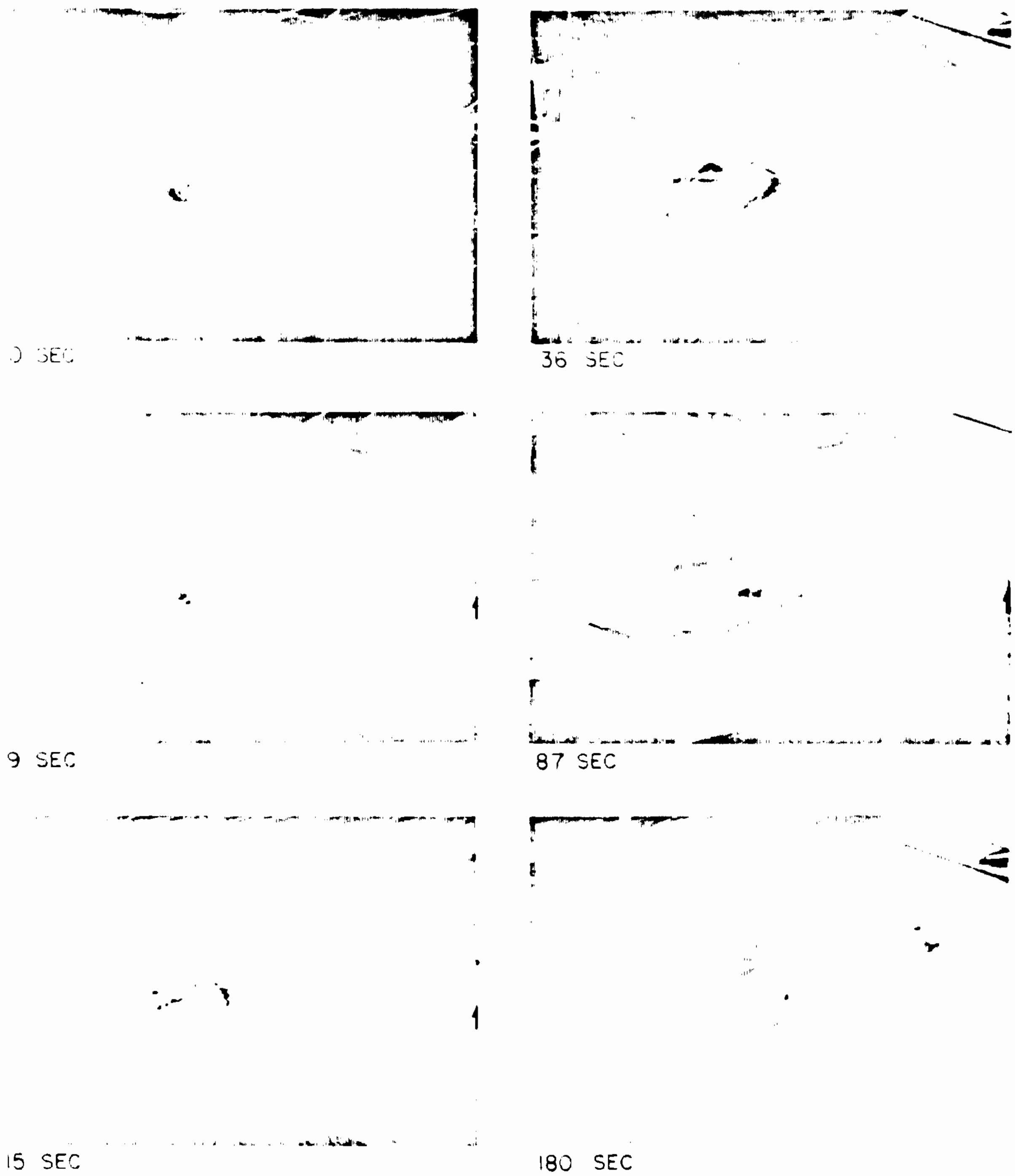


CHARGE WEIGHT = 2,560 LB
CHARGE DEPTH = 6.79 FT
SCALED DEPTH = 0.496 FT/LB$^{1/3}$

Fig. 2.3 Aerial Photographs - Round HE-3

## 2.2 GROUND-RISE

High-speed motion picture photography is necessary for the study of the ground rise and breakthrough of gases from an underground explosion. Fastax cameras, operated at speeds up to 1540 frames per second, were used at Dugway by the Industrial Research Institute of the University of Denver. When possible, measurements were made of the time to the initial ground rise, the velocity and maximum height of the ground rise, and the time of breakthrough. Fastax records were also obtained at Nevada by the Sandia Corporation, but similar measurements are not available at this time.

In general, the data obtained from the Dugway dry clay[1] and dry sand[2] photographic records show that the time to the initial rise of the ground increases with increasing charge depth and increasing charge weight. The height of the ground rise at which initial venting occurs appears to increase with increasing charge depth to a maximum, and then to decrease for deeper charges. These results are shown graphically in Figure 2.4.

The velocity of ground-rise is approximately the same for charges fired at the same scaled depth in the same type of soil and decreases with increasing charge depth. Velocity data are summarized in Table 2.1.

## 2.3 SMOKE CROWN

The smoke crown develops from what appears to be a partial venting of explosion products. The time to this initial breakthrough increases with increasing charge depth. Measurements obtained in dry sand are presented in Table 2.2.[3]

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1 Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 1, Dry Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-293, 1 Aug. 1951, pp 5-1 to 5-11.

2 Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 2, Dry Sand, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-293, 1 Oct. 1951, pp 5-1 to 5-16.

3 Ibid., pp 5-4 to 5-10.

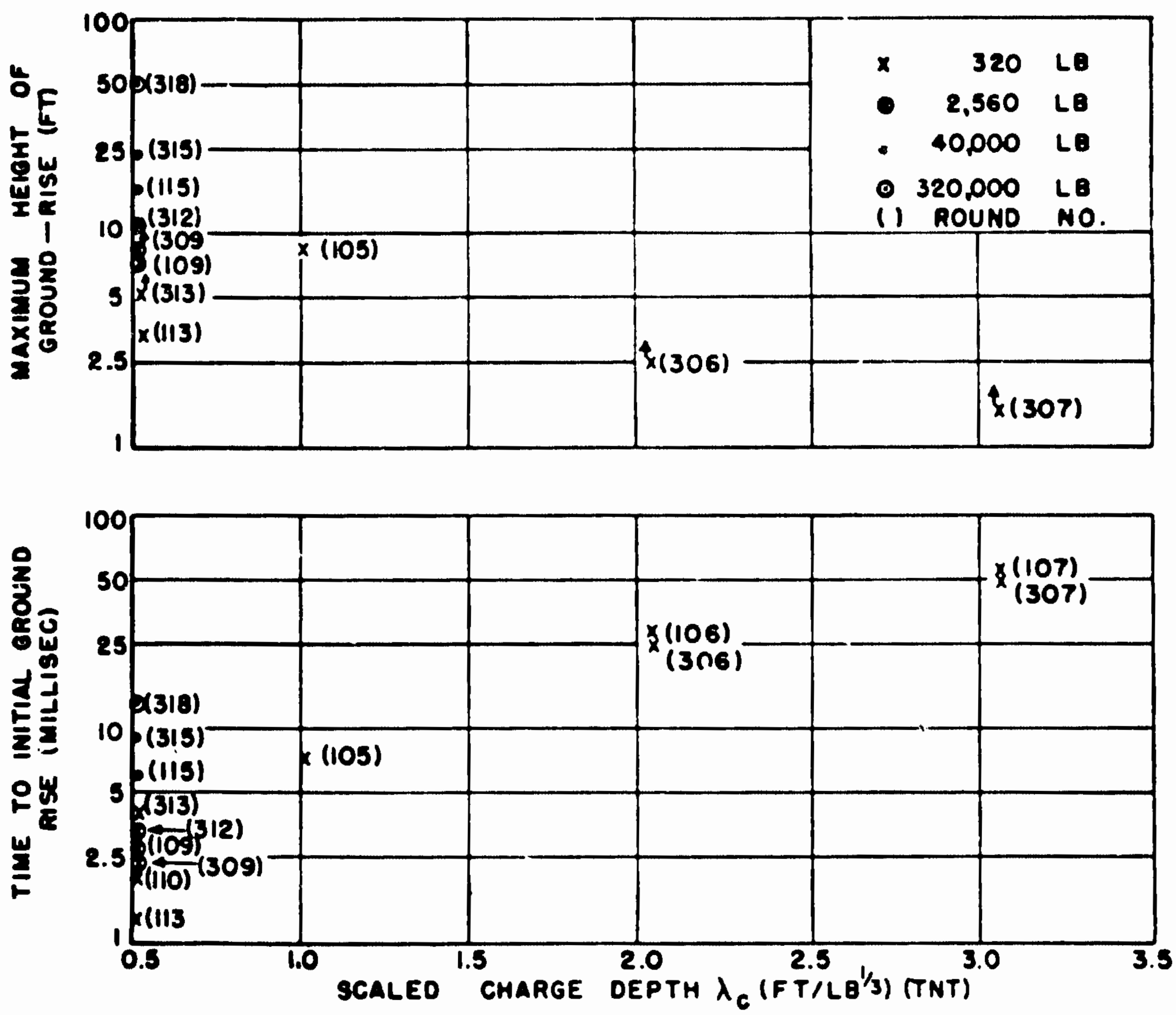


Fig. 2.4 Time to Initial Ground-Rise and Maximum Height of Ground-Rise vs Scaled Charge Depth

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TABLE 2.1

Velocity of Ground-Rise in Dry Clay and Dry Sand

| Round | Soil Type | Charge Wt. (lb TNT) | Scaled Depth ($ft/lb^{1/3}$) | Velocity of Ground-Rise (ft/sec) |
|---|---|---|---|---|
| 110 | Dry Sand | 320 | 0.512 | 730 |
| 113 | Dry Sand | 320 | 0.512 | 680 |
| 109 | Dry Sand | 2,560 | 0.512 | 510 |
| 115 | Dry Sand | 40,000 | 0.512 | 710 |
| 105 | Dry Sand | 320 | 1.02 | 220 |
| 106 | Dry Sand | 320 | 2.05 | 70 |
| 107 | Dry Sand | 320 | 3.07 | 30 |
| 313 | Dry Clay | 320 | 0.512 | 770 |
| 309 | Dry Clay | 2,560 | 0.512 | 780 |
| 312 | Dry Clay | 2,560 | 0.512 | 834 |
| 315 | Dry Clay | 40,000 | 0.512 | 770 |
| 318 | Dry Clay | 320,000 | 0.512 | 780 |
| 306 | Dry Clay | 320 | 2.05 | 57.6 |
| 307 | Dry Clay | 320 | 3.07 | 18.8 |

TABLE 2.2

Time of Breakthrough for Charges Fired in Dry Sand

| Round | Charge Weight (lb TNT) | Scaled Depth ($ft/lb^{1/3}$) | Breakthrough (millisec) |
|---|---|---|---|
| 113 | 320 | 0.512 | 5.8 |
| 105 | 320 | 1.02 | 42 |
| 106 | 320 | 2.05 | 700 |
| 107 | 320 | 3.07 | >1300 |
| 109 | 2,560 | 0.512 | 15.4 |
| 115 | 40,000 | 0.512 | 31 |

The smoke crown seems to consist of a mixture of dust and smoke particles and behaves like an aerosol with a relatively low density. It falls and mixes with the su[illegible] cloud when charges are fired at $\lambda_c = 0.5$ $ft/lb^{1/3}$ with a moderate wind (see Section 2.5) and for all deeper shots.

At $\lambda_c$ = 2.0 ft/lb$^{1/3}$ and at greater depths, the jet does not break through the smoke crown and its general appearance is that of a dome-shaped dust and smoke cloud. It is difficult to distinguish the smoke crown from the dirt column beneath it at these scaled charge depths.

For charges fired at a scaled depth less than 0.5 ft/lb$^{1/3}$ (and rounds fired at a $\lambda_c$ of 0.5 ft/lb$^{1/3}$ with a light wind), the smoke crown does not fall appreciably but becomes diffuse and moves downwind, mixing with the rising surge cloud until they become indistinguishable.

The initial rise of the smoke crown for Round HE-3 in Nevada is shown in Figure 2.5.

## 2.4 COLUMN

The dirt column rises from the ground following the initial smoke cloud. For charges fired at scaled depths of 1.0 ft/lb$^{1/3}$ or less the column is initially narrower at the base than at the top, but expands radially until the walls are almost vertical. The column walls are relatively smooth until this time, but develop a spiky appearance and then become diffuse and less sharply defined. Dirt clods are thrown out radially through the column and follow a downward trajectory. In dry hard-packed soils, such as at the Nevada test site, dust trails from the soil conglomerates may obscure the further behavior of the column. The assumptions are made that the dust aerosol in the column drops vertically and flows outward radially along the ground as the base surge and that the heavy radial throwout does not contribute to the surge flow.

For charges fired at scaled depths of 2.0 ft/lb$^{1/3}$ or more, the column is initially dome-shaped, reaching its greatest diameter at the base. The column expands until the walls are approximately vertical and little or no radial throwout is observed.

At all depths studied, the rate of expansion of the column base is approximately linear until the walls become spiky and diffuse. For scaling purposes, the maximum column diameter at the base ($D_{max}$) is defined as the size attained when the linear horizontal growth ends. (The column subsequently appears to grow rapidly because of throwout and dust obscuration.) Column height (C) is measured to the base of the smoke crown and, for scaling, the assumption is made that any part of the column extending into the smoke crown is diffuse and has a negligible effect on the growth of the base surge.

As accurate measurements of maximum column height and diameter can be obtained solely from motion picture records, such data are not available for all of the Dugway tests.

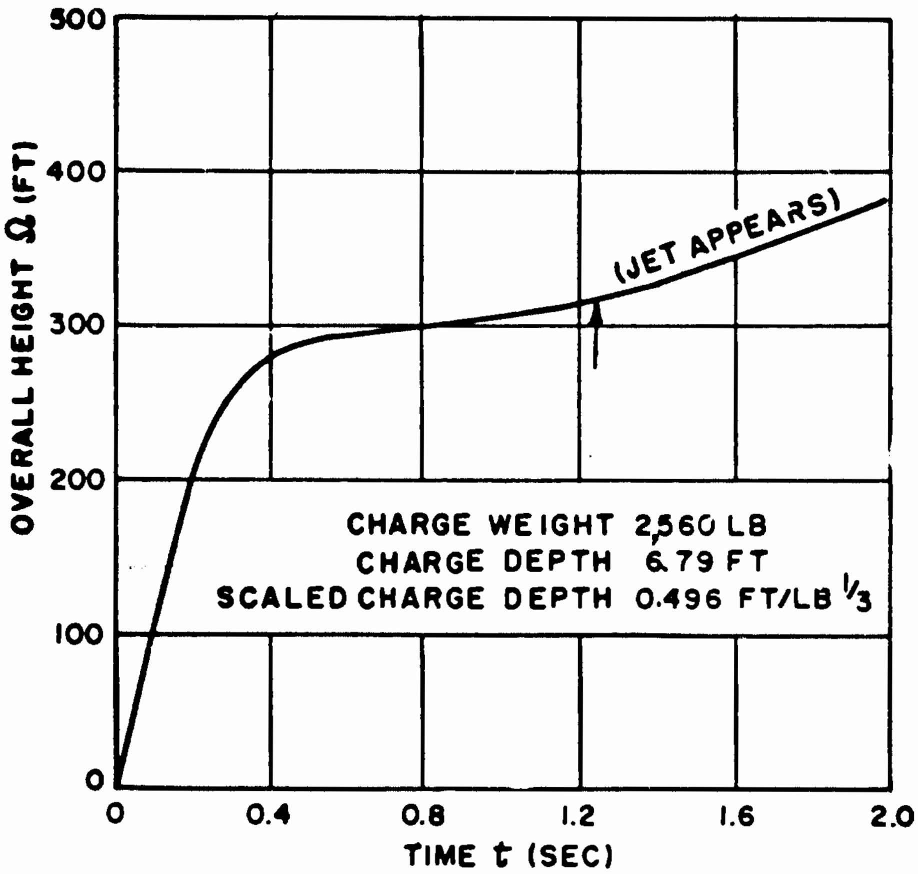


Fig. 2.5 Height of Smoke Crown vs Time - Round HE-3

As shown in Figure 2.6, the relation between $D_{max}$ and charge weight may be expressed by a power formula for buried charges fired at the same scaled depth. Column diameter apparently reaches a maximum when the charge is half underground ($\lambda_c = 0$) or near that depth. For rounds fired with the upper surface of the charge tangent to the ground and for deeper shots, $D_{max}$ increases with increasing depth to a maximum at about $\lambda_c = 1.0$ and decreases from there on.

The relation between maximum column diameter and charge weight for a scaled depth of $\lambda_c = 0.512$ ft/lb$^{1/3}$ in dry clay may be expressed as:

$$D_{max} = 10.9\ W^{0.304} \quad (\lambda_c = 0.512\ \text{ft/lb}^{1/3}) \tag{2.1}$$

where $D_{max}$ = maximum column diameter, ft
$W$ = charge weight, lb (TNT)

At a scaled depth of 0.135 ft/lb$^{1/3}$ in dry clay, the shallowest depth at which the charge was not exposed to the air, the relation is:

$$D_{max} = 8.38\ W^{0.304} \quad (\lambda_c = 0.135\ \text{ft/lb}^{1/3}) \tag{2.2}$$

Similar expressions can be obtained for $C_{max}$. (See Fig. 2.7.) As maximum column height and maximum column diameter are equal at scaled depths of 0.512 ft/lb$^{1/3}$, the formulas are the same. However, since column height changes more rapidly with charge depth than does column diameter, agreement is not obtained at other values of $\lambda_c$. The formulas for scaled depths of 0.512 and 0.135 ft/lb$^{1/3}$ in dry clay are:

$$C_{max} = 10.9\ W^{0.304} \quad (\lambda_c = 0.512\ \text{ft/lb}^{1/3}) \tag{2.3}$$

$$C_{max} = 5.71\ W^{0.304} \quad (\lambda_c = 0.135\ \text{ft/lb}^{1/3}) \tag{2.4}$$

where $C_{max}$ = maximum column height, ft
$W$ = charge weight, lb (TNT)

Column heights reach a maximum at about $\lambda_c = 1.0$ ft/lb$^{1/3}$ and are less for charges shallower or deeper than this.

The ratio of maximum column height to maximum column diameter is important for scaling the radial growth of the base surge. (See Chap. 4.) Average values of $C_{max}/D_{max}$ are given in Fig. 2.8, for the range of scaled

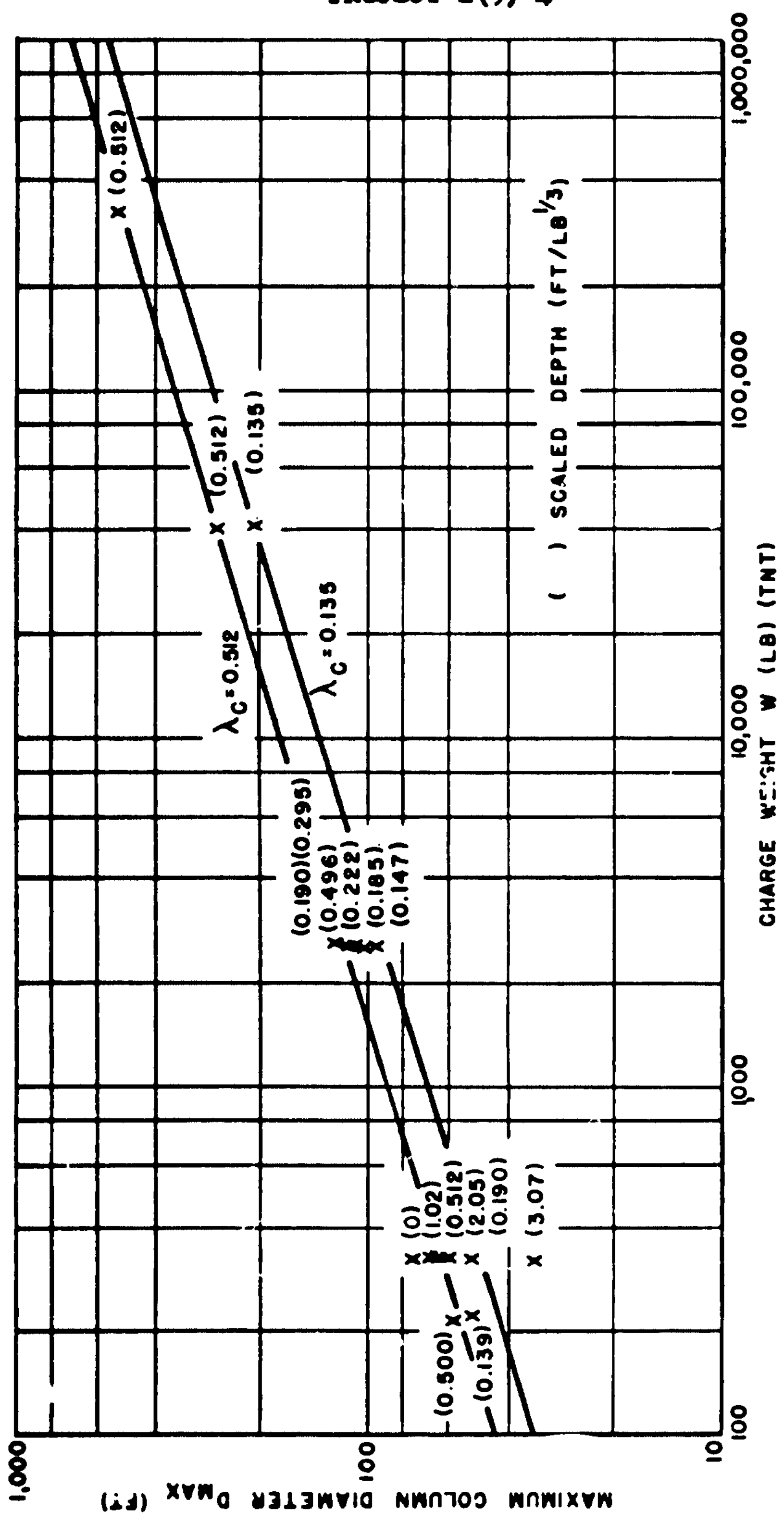


Fig. 2.6 Maximum Column Diameter vs Charge Weight

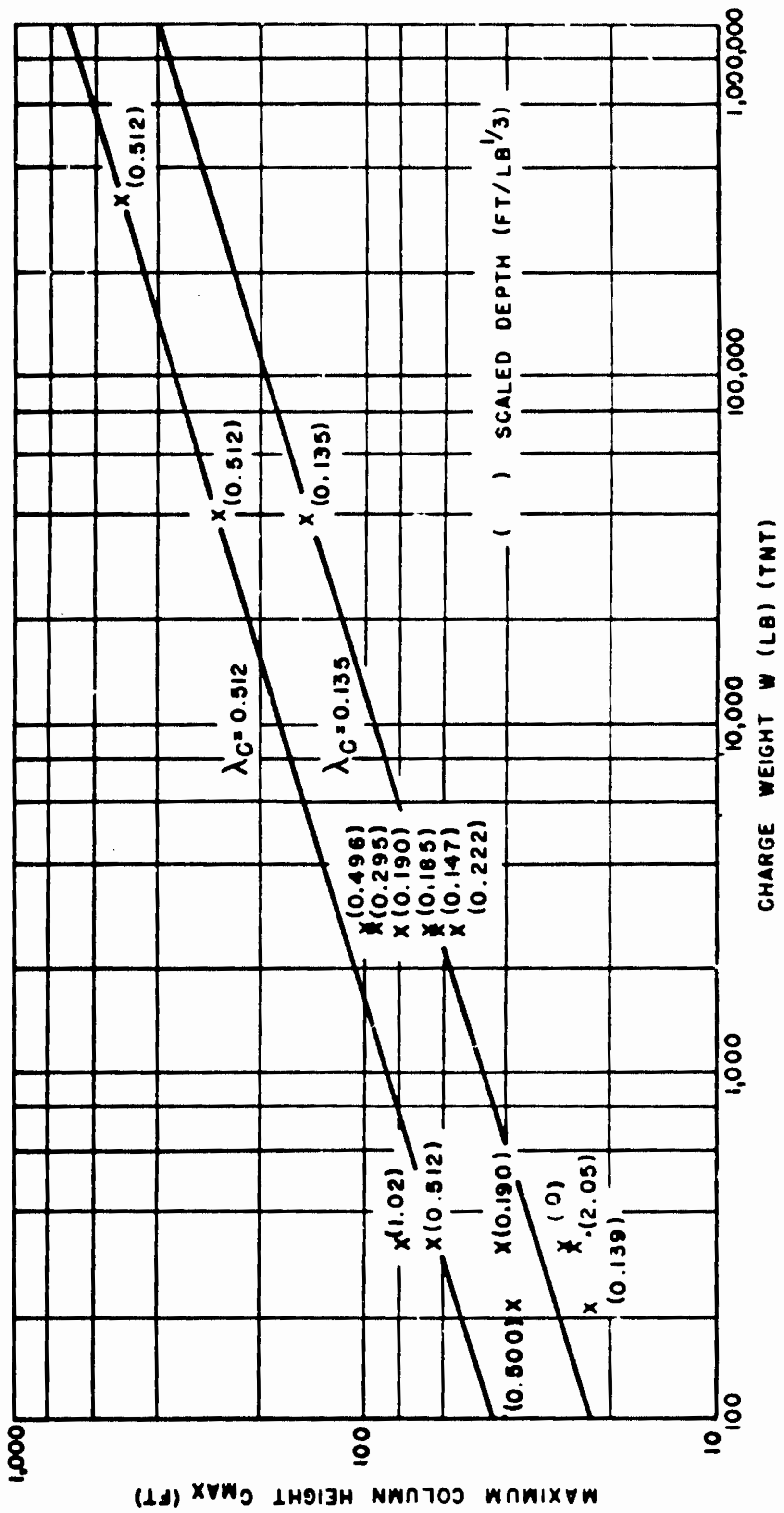


Fig. 2.7 Maximum Column Height vs Charge Weight

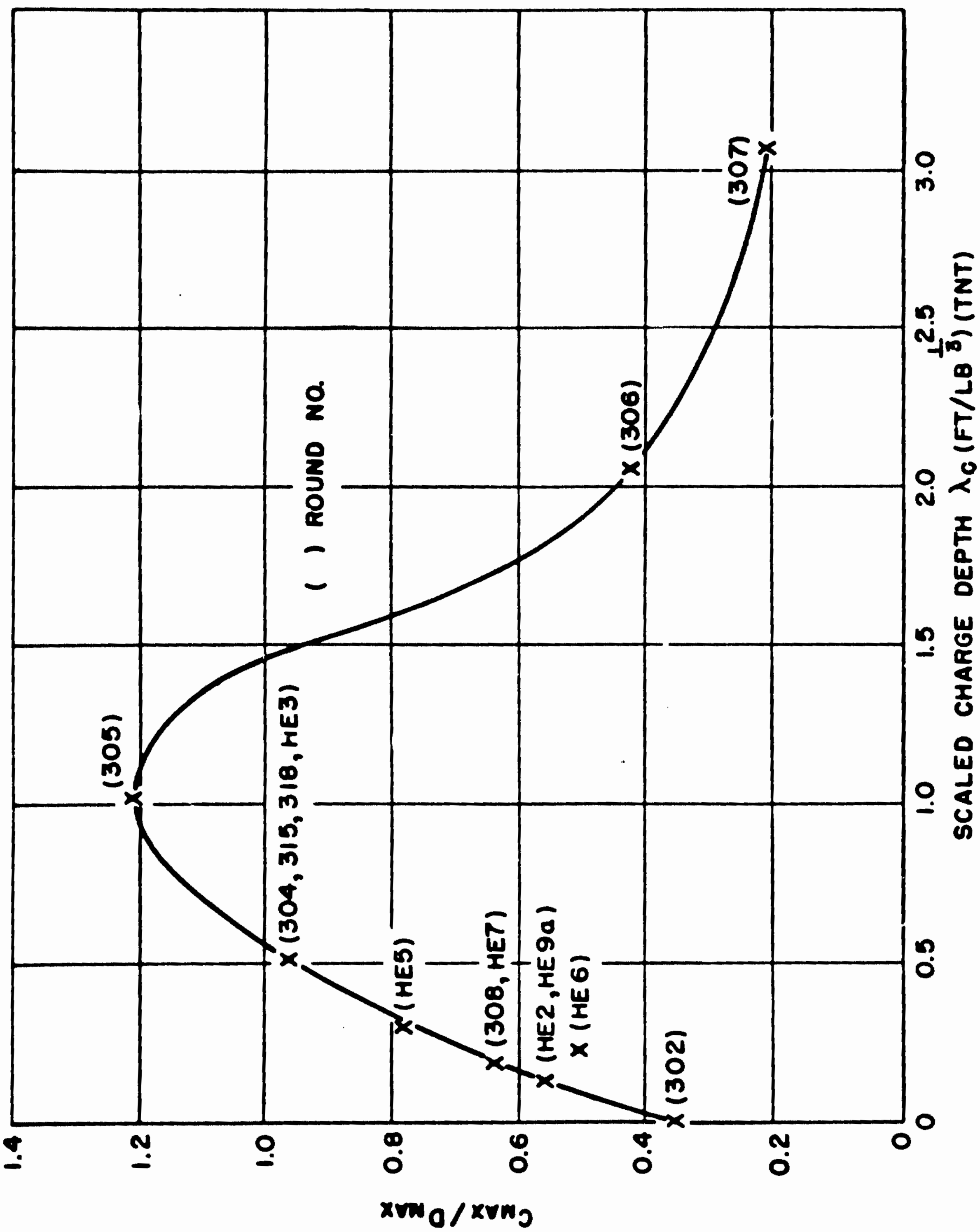


Fig. 2.8 Ratio of Maximum Column Height to Maximum Column Diameter vs Scaled Charge Depth

depths available in dry clay at Dugway and at Nevada, and indicate a maximum value of this ratio at about $\lambda_c = 1.0$ ft/lb$^{1/3}$.

The general structure of the visible surface phenomena indicates that the column is a hollow cylinder,[4] except possibly at charge depths of 2.0 ft/lb$^{1/3}$ or more, when the central jet does not vent through the ground surface. It is difficult to distinguish the column from the smoke crown at these depths.

## 2.5 JET

A central jet of explosion gases and smoke appears for charges fired at scaled depths ranging from zero to a depth somewhat greater than 1.0 ft/lb$^{1/3}$, though the jet is relatively low and narrow at the deeper positions in this range. When charges are fired at scaled depths of 2.0 ft/lb$^{1/3}$ and deeper, the jet does not appear.

TNT charges produce a black jet, which is clearly defined at first and rises at a high velocity, due to the rapid expansion of the explosion gases. The outline of the black cloud is sharp and it has a turbulent appearance.

The rate of rise then decreases, due to turbulent mixing with the surrounding air, and the outer edges become diffuse. However, the jet continues to rise at a fairly high rate, as a result of its buoyancy.

When the buoyant lifting ceases, the jet cloud may rise or fall, depending upon its density and atmospheric conditions. If the bulk density is high enough and the smoke and soil particles are of the proper size and spacing, a downward density flow will be started and the cloud will drop and flow outward along the ground into the base surge. If the bulk density is nearly the same as the density of the air, the jet cloud will be subject to lift and dispersal by atmospheric convection and turbulence.

The scaled depth of 0.5 ft/lb$^{1/3}$ appears to be critical in this regard. At this firing condition, the jet remains partially airborne if the wind is light, but falls almost completely with a strong wind. The contribution of the jet to the base surge decreases as charges are fired in relatively shallower positions, and at $\lambda_c$ = zero, the jet remains

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[4] V. Salmon, Throw-Out Phenomena in Underground Explosions, Status Report No. 6, Contract N7onr32104, Stanford Research Institute Project 317, 29 March 1951, p 2.

completely airborne and is dispersed by turbulent atmospheric motion.

For charges fired at scaled depths greater than 0.5 ft/lb$^{1/3}$, virtually the entire jet deposits on the ground or enters the base surge in a short time. The contribution of the jet to the surge cloud decreases with increasing depth and is unknown when the jet does not vent completely through the smoke crown.

For scaling purposes, the maximum jet height ($J_{max}$) is defined as the limit of the buoyant rise of the jet. This is measured, somewhat subjectively, by examination of motion picture records, but may sometimes be obtained from plotted data of jet height vs time. For shallow charges $J_{max}$ may coincide with the point at which the jet growth becomes linear, beyond which the growth is due to turbulent diffusion. With deeper charges, $J_{max}$, as defined herein, should be approximately equal to the greatest height attained by the jet.

The maximum jet heights for the Dugway dry clay tests and the Nevada HE tests are shown in Fig. 2.9 as functions of charge weight. For the scaled depth of 0.512 ft/lb$^{1/3}$ the relation between $J_{max}$ and charge weight may be expressed by the following formula:

$$J_{max} = 116\, W^{0.224} \quad (\lambda_c = 0.512 \text{ ft/lb}^{1/3}) \qquad (2.5)$$

where $J_{max}$ = maximum jet height, ft
$W$ = charge weight, lb (TNT)

$J_{max}$ does not vary greatly for shallow charges, and the same formula may be applied to obtain an approximate maximum jet height, with about a 15% possible error, for charges fired between the scaled depths of zero and 0.6 ft/lb$^{1/3}$ in dry clay.

If maximum overall height is plotted against $\lambda_c$, as in Fig. 2.10, a good relation can be obtained for the maximum heights reached by the surface phenomena produced by the deeper 320 lb charges in dry clay (scaled depth greater than 0.5 ft/lb$^{1/3}$), although overall height coincides with jet height at scaled depths of 0.5 and 1.0 ft/lb$^{1/3}$ and represents height of the smoke crown for deeper charges. The formula is:

$$\Omega_{max} = 774\, e^{-1.13\,\lambda_c} \quad (320 \text{ lb, dry clay, } \lambda_c > 0.5 \text{ ft/lb}^{1/3}) \qquad (2.6)$$

where $\Omega_{max}$ = maximum overall height, ft
$\lambda_c$ = scaled charge depth, ft/lb$^{1/3}$

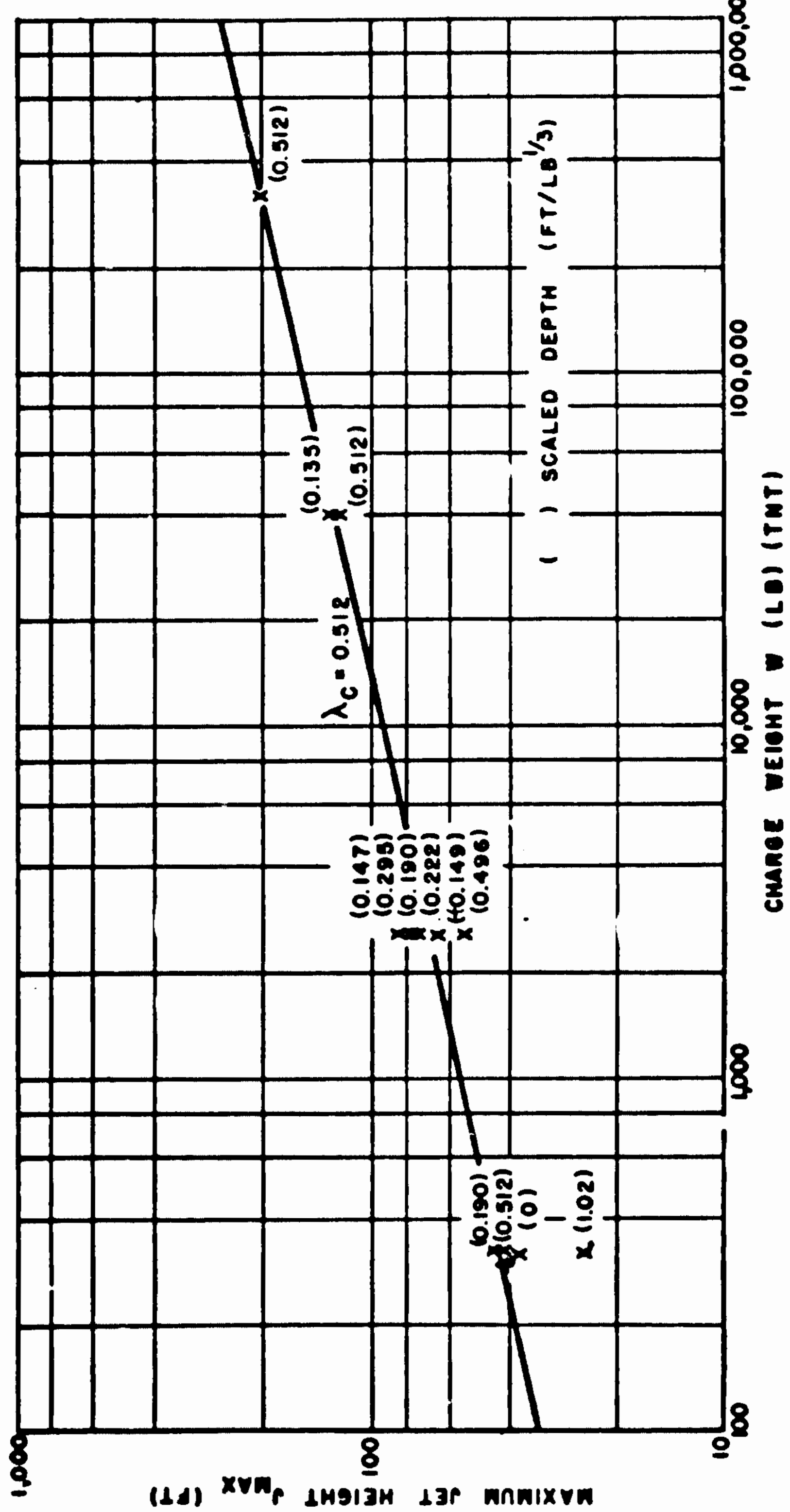


Fig. 2.9 Maximum Jet Height vs Charge Weight

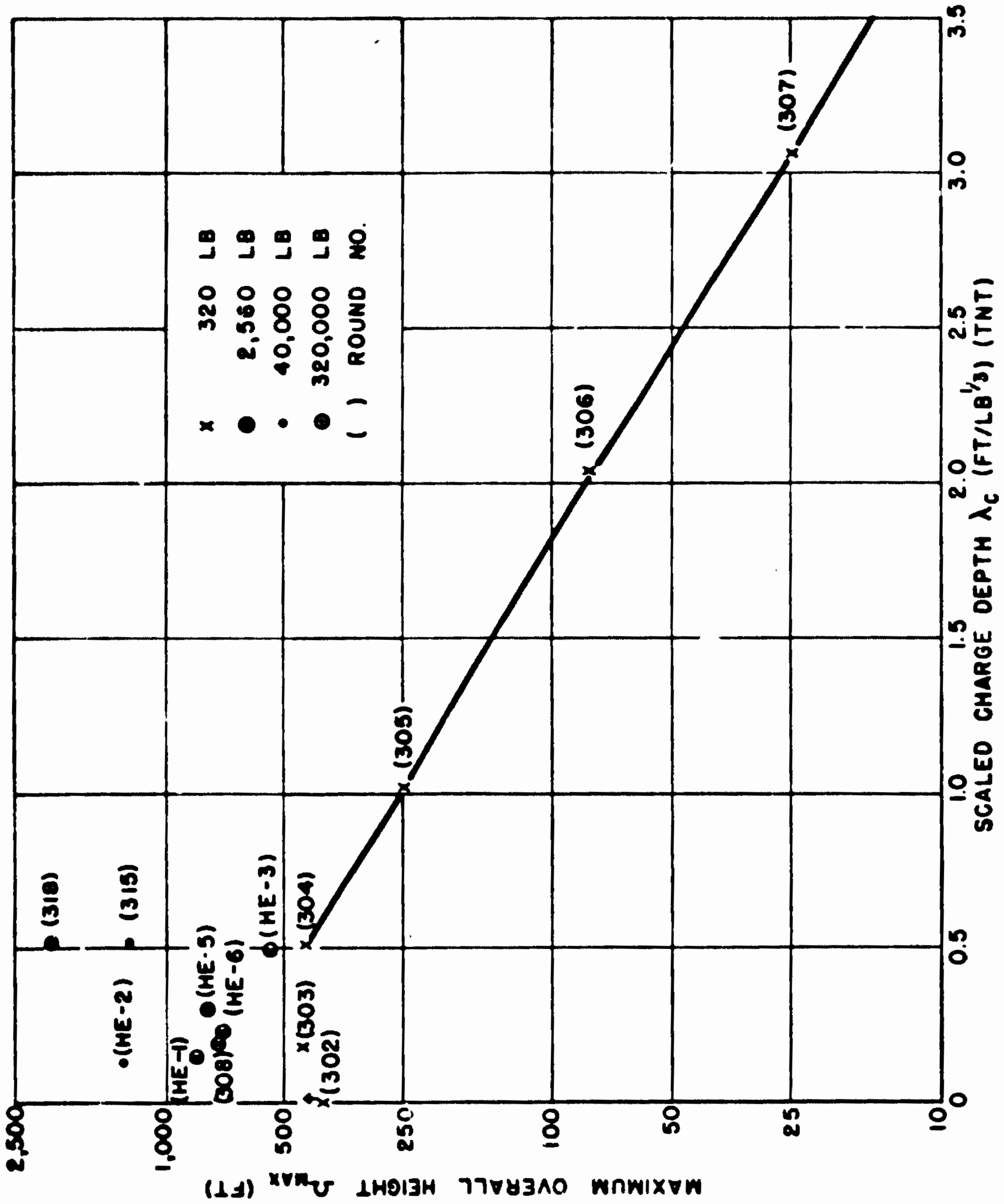


Fig. 2.10 Maximum Overall Height vs Scaled Charge Depth

The data indicate that the maximum scaled depth for the formation of such surface phenomena increases with increasing charge weight.

The vertical growth of jets from 320 lb and 2560 lb charges is presented in Figs. 2.11 and 2.12 and a comparison of the jets from charges of different weights at the same scaled depth is shown in Fig. 2.13. When possible, the ends of the growth curves indicate $J_{max}$, as defined herein. As the initial rapid rise of the jet can only be resolved with motion picture photography, jet records are not available for the dry sand and wet clay programs.

The available data show that the jet velocity is greatest for charges fired at a scaled depth of about 1 [illegible] ft/lb$^{1/3}$ and decreases for charges placed at shallower or deeper positions. The records of Rounds 306 and 307 represent height of the smoke crown, but are included in Fig. 2.11 for comparison with shallower shots. Initial jet velocity increases with increasing charge weight, for charges fired at the same scaled depth.

After the buoyant rise of the jet has ended, the top of the jet cloud represents the overall height ( $\Omega$ ) of the surface phenomena. Records of the changes in overall height are given in Figs. 2.14, 2.15 and 2.16. Overall heights of dry sand and wet clay rounds are included in these charts.

When charges were fired at the same scaled depth in different types of soil, the wet clay rounds produced the most rapidly rising jet clouds and dry clay the slowest rising jet clouds, with charges in dry sand generally intermediate between the two.

However, the overall height is greatly affected by atmospheric conditions, as indicated by the different curves shown for charges fired at the same scaled depth in the same soil type. Both jet height and overall height are influenced by wind and atmospheric turbulence. The effects of wind and its variations in time and space are complex but, in general, strong winds have the effect of holding the jet down. Probably a surface wind of at least 15 mph, accompanied by gustiness and an increase of speed with height, is needed to hold back the jet and force it down rapidly, when charges are fired at scaled depths of 0.5 ft/lb$^{1/3}$ or greater. (See Fig. 3.11.) Atmospheric conditions may have effects of different relative importance for charges greater than 320,000 lb or less than 320 lb.

Wind effects are discussed further in Section 5.2.

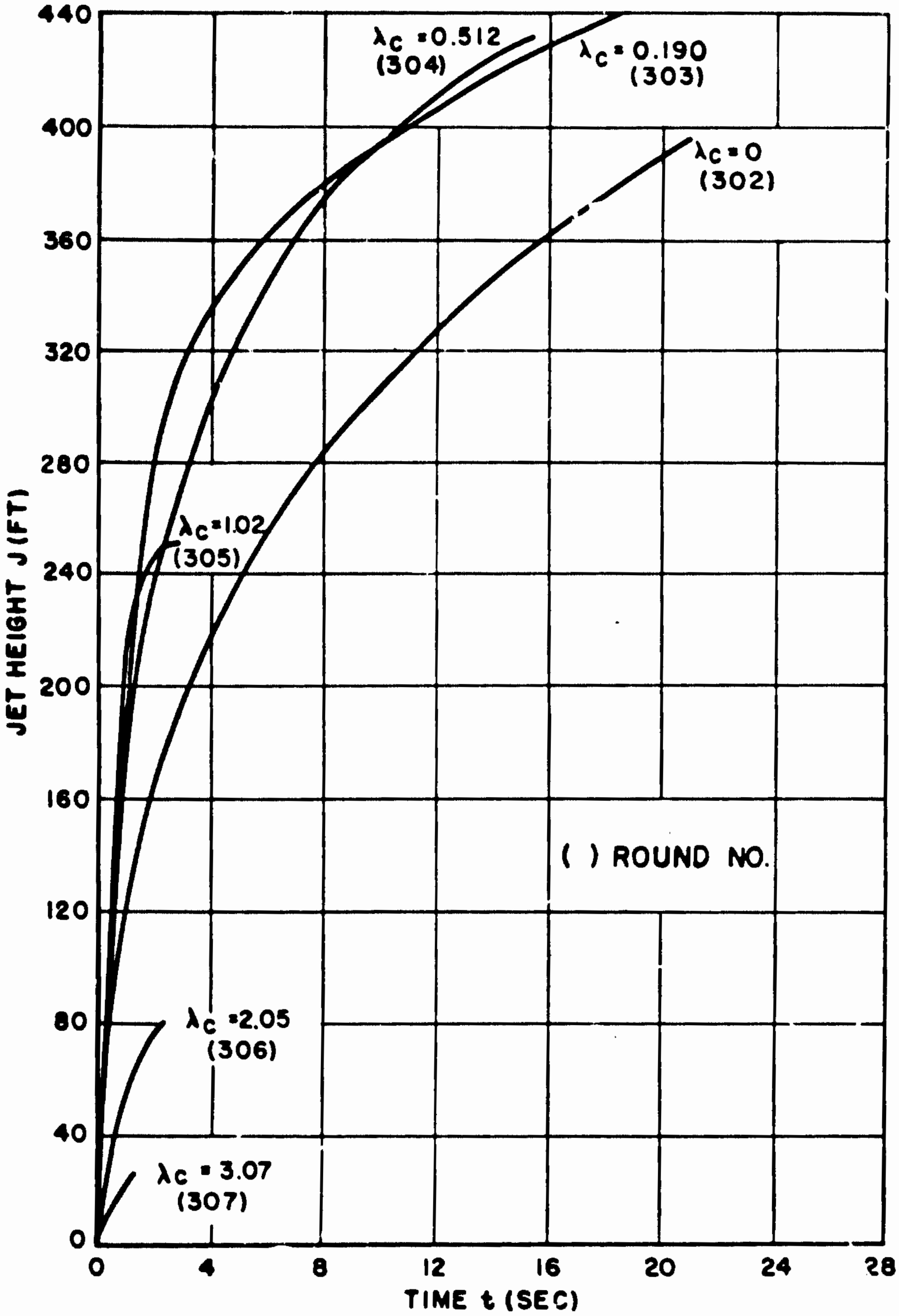


Fig. 2.11 Jet Height vs Time - 320 Lb TNT Charges

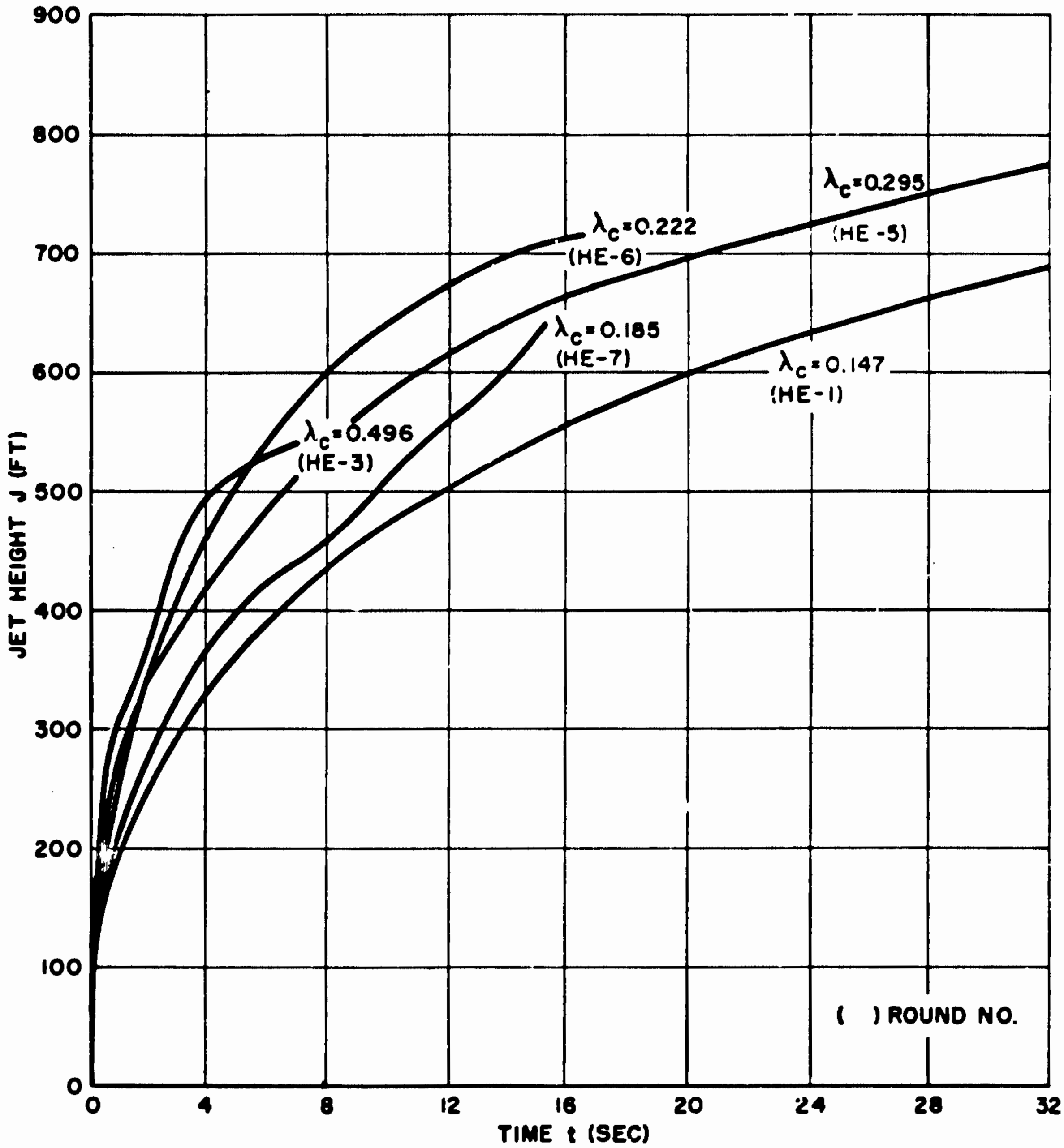


Fig. 2.12 Jet Height vs Time - 2,5600 Lb TNT Charges

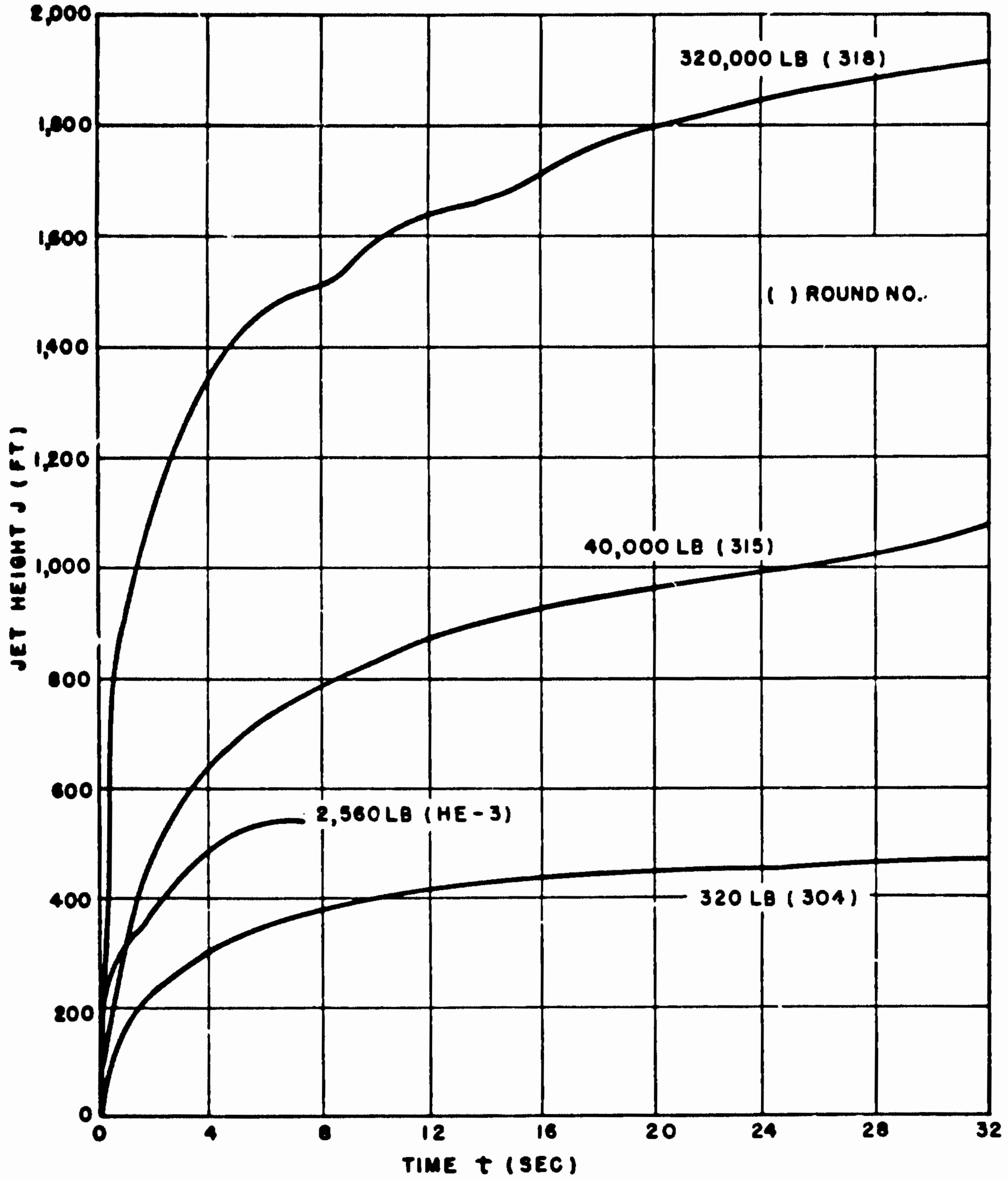


Fig. 2.13 Jet Height vs Time - Scaled Depth = 0.5 Ft/Lb$^{1/3}$ (TNT)

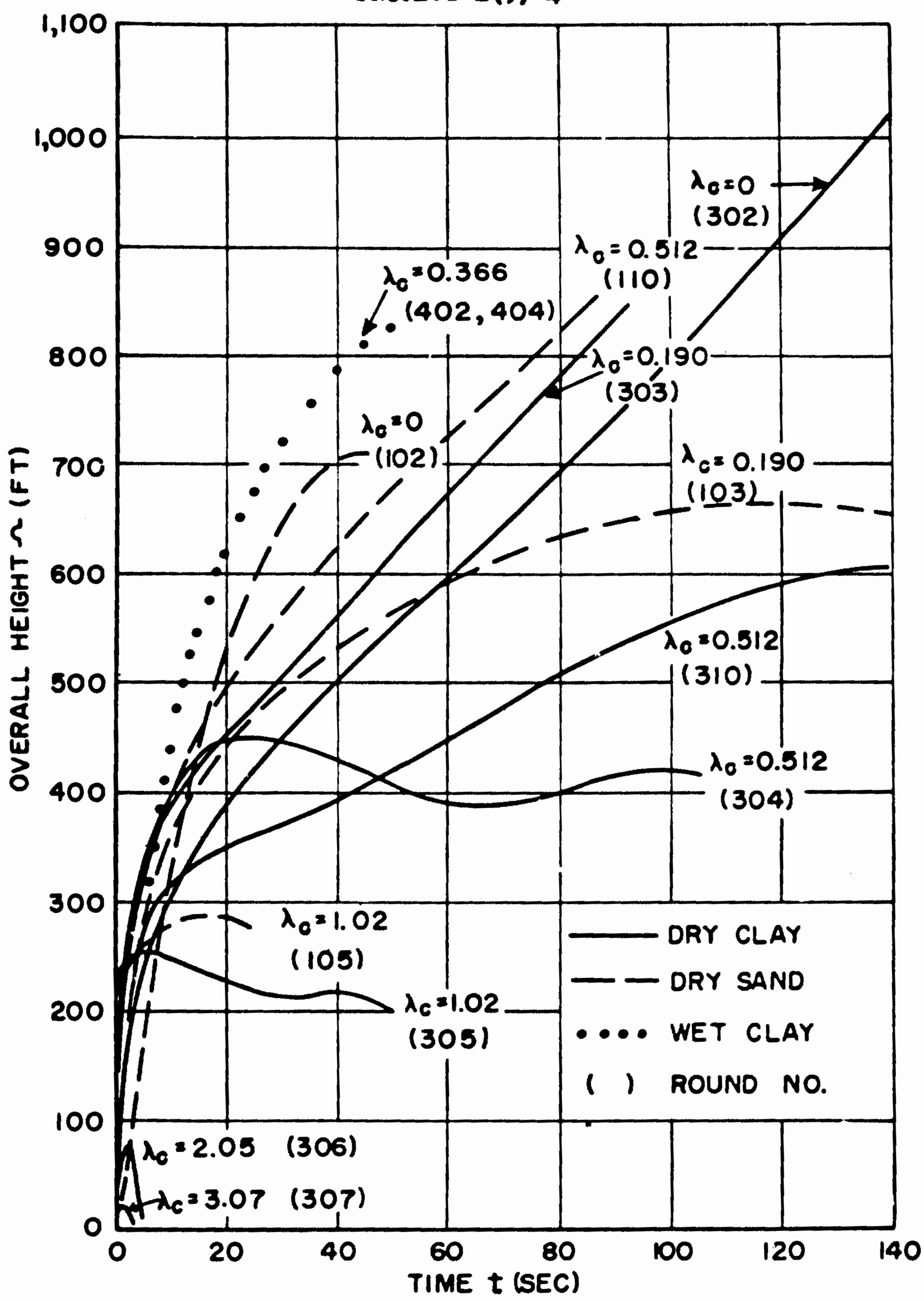


Fig. 2.14 Overall Height vs Time - 320 lb TNT Charges

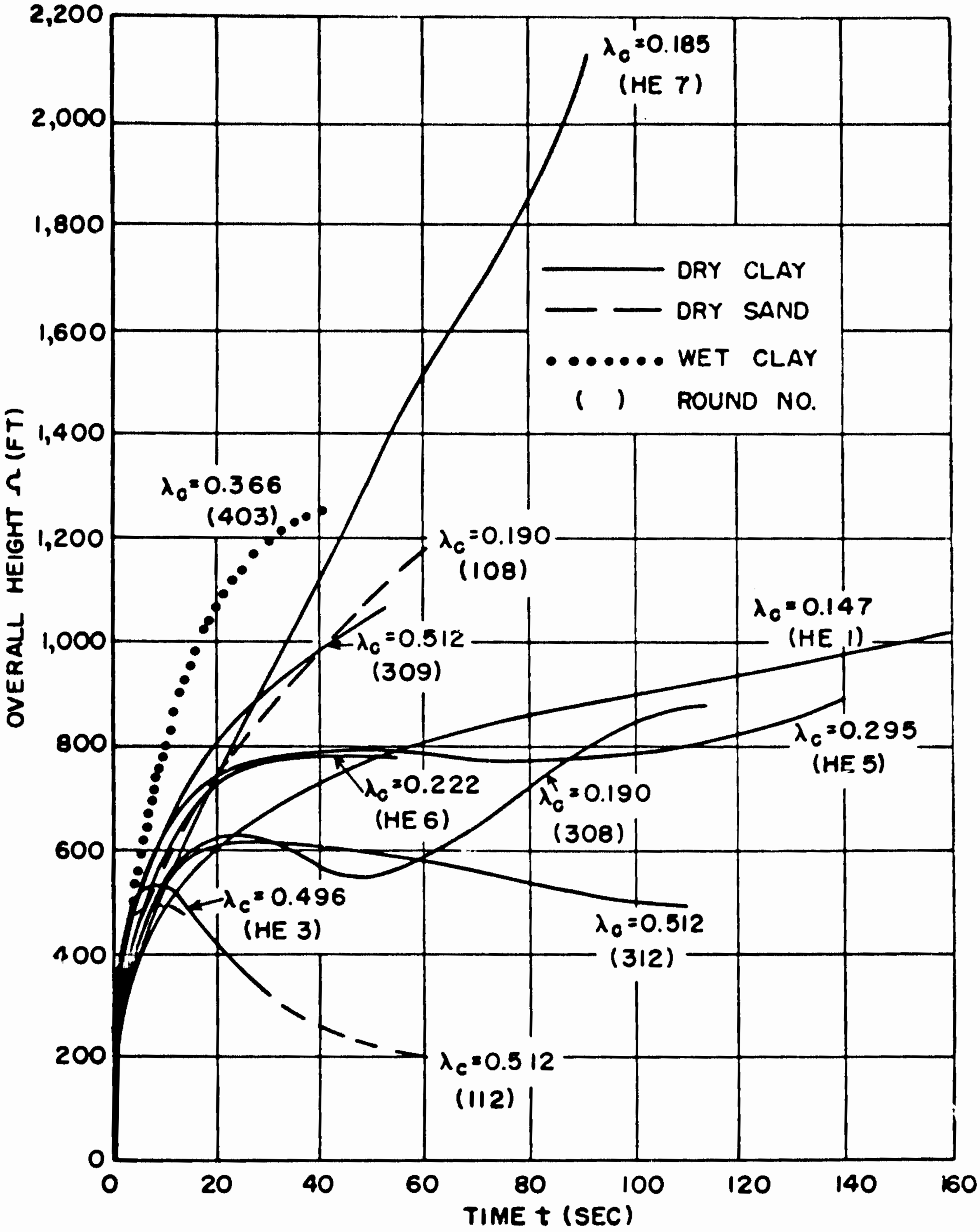


Fig. 2.15 Overall Height vs Time - 2,560 Lb TNT Charges

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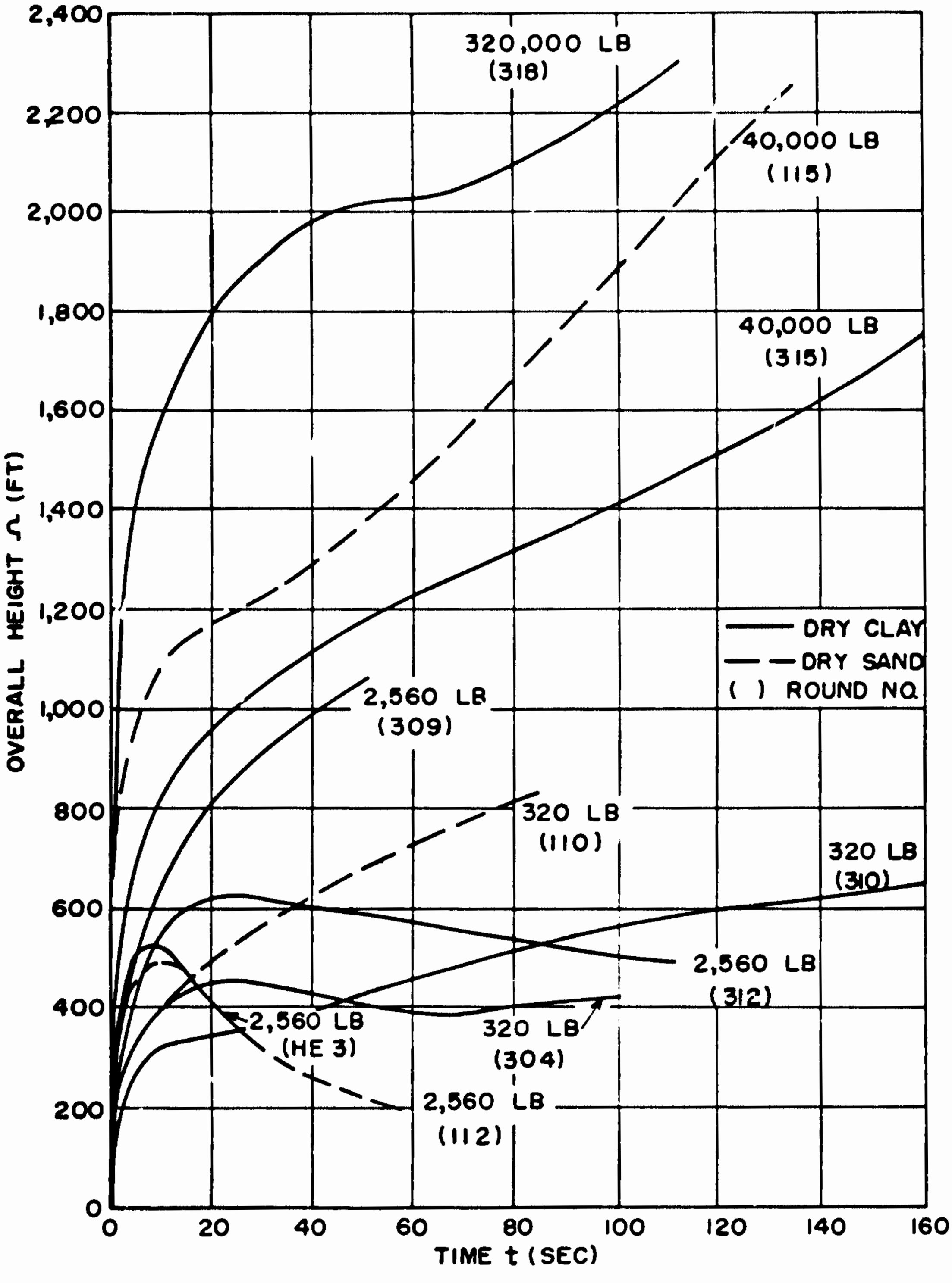


Fig. 2.16 Overall Height vs Time - Scaled Depth = 0.5 Ft/Lb$^{1/3}$ (TNT)

## 2.6 CHARGES ON THE SURFACE

One record is available for a charge fired on the surface of the ground: Round HE-4, at Nevada, was a 2560 lb charge, detonated at $\lambda_e = -0.149$ ft/lb$^{1/3}$.

The explosion scooped out a shallow crater, about 2 ft deep and 16 ft in diameter,[5] and the surface shock wave raised considerable surface dust. An irregularly shaped cloud formed and rose relatively slowly, while a thin pillar of dust trailed beneath it. The upper cloud was divided into two distinct portions, a black smoke cloud and a light dust cloud, which gradually merged into a single diffuse mass. The trailing dust pillar soon became tenuous and the whole cloud dissipated within a half hour. No base surge formed at this charge position.

Some of the important features of the surface phenomena are shown in Fig. 2.17.

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[5] D. C. Campbell, LCDR, USN, Tests and Observations on Craters and Base Surges, JANGLE Report 1(9)-3, 1 Nov. 1951.

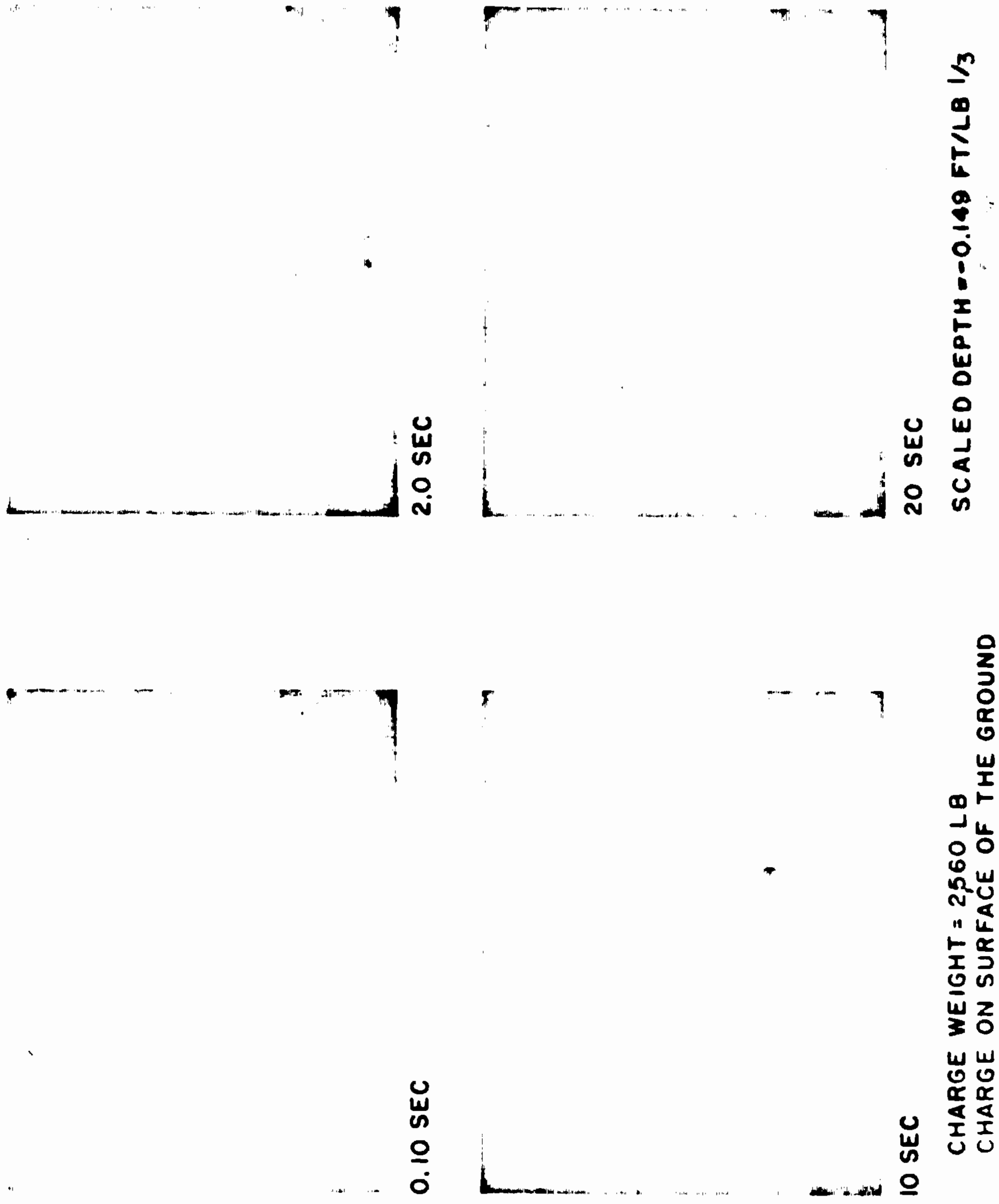


Fig. 2.17 Surface Phenomena - Round HE-4

# CHAPTER 3

# BASE SURGE

## 3.1 METHOD OF FORMATION AND DISSIPATION

The roughly cylindrical earth column that is formed above the ground when the explosive gases vent consists of a mixture of soil particles of a wide range of size. The larger clods or aggregates drop back but the smaller particles entrain air because of their high concentration and do not fall individually. It is assumed that the dense aerosol falls at a rate considerably greater than the terminal velocities of the individual particles and flows outward radially at the base of the column to form the base surge. The entire suspension of dust in air behaves in the manner of a homogeneous fluid with a mean density somewhat higher than the density of the surrounding air.

This type of phenomenon is not confined to explosions and is known as bulk subsidence. It has been investigated on a laboratory scale at the Woods Hole Oceanographic Institution[1] and Stanford University.[2] The limited data available indicate that the ratio of current velocity to particle velocity is greatest for very small particles at a high concentration and was as large as 10,000 with smoke containing one million particles of ammonium chloride per cc (particle radius 0.1 micron).[3]

When the falling aerosol changes its direction of flow from vertical to horizontal at the base of the column, the larger particles do not follow the sudden bending of the streamlines but continue their downward path and are deposited upon the ground. A tall dense column will fall rapidly and deposit particles of a wide range of size in this manner, but a shallow column of low density will deposit only the relatively large particles.

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[1] A. B. Arons, G. Wertheim, and M. Krumholz, Density Currents Induced by Streams of Falling Particles, Woods Hole Oceanographic Institution, Woods Hole, Mass., NAVORD Report 485, 21 March 1951, pp 1-29.

[2] S. W. Grinnell, W. A. Perkins and F. X. Webster, Bimonthly Report 3 of Chemical Warfare Service Research and Development Program, Contract No. W-18-035-CWS-1256, Stanford Univ., Calif., May - June 1946, pp 15-24.

[3] Ibid., p 16.

After the column has settled and flowed outward, the clouds of dust and smoke particles constituting the jet and smoke crown may fall and propagate into the surge. These clouds are lighter than the column and drop more slowly, but contribute additional material to the base surge.

The successful use of Froude scaling in the study of the base surges produced by underwater[4] and underground explosions (see Chap. 4) indicates that the initial radial growth of the base surge is controlled by gravitational and inertial forces. When the particle concentration is reduced by expansion of the surge, further growth is controlled by eddy diffusion. The point at which the latter mechanism becomes the more important of the two depends upon meteorological as well as firing conditions.

As the rate of radial growth of the base surge decreases, the heavier particles settle under gravity until a relatively stable aerosol remains. At this stage, the particles are probably less than a few microns in size and the Stokes' Law rate-of-fall is small. The tenuous dust cloud is then subject to atmospheric turbulence and may remain airborne for a considerable period of time.

## 3.2 EFFECTS OF SOIL AND CHARGE DEPTH

The rate of growth and maximum extent of the base surge depend upon charge weight, charge depth, character of soil, and meteorological conditions.

As the base surge is often irregular in shape initially and is further distorted by wind and atmospheric turbulence, mean values of the radius are used in the following pages to indicate the growth of the surge. Similar records of two or more rounds are averaged. Figure 3.1 shows that the maximum average rate of surge growth and probably the greatest surge extent for 320 lb charges in dry clay or dry sand occurs at a 7 ft charge depth ( $\lambda_c$ = 1.02 ft/lb$^{1/3}$). A similar trend is indicated in Figure 3.2 for 2560 lb charges, though no rounds were fired at scaled depths greater than 0.512 ft/lb$^{1/3}$. The effect of charge weight is shown for rounds fired at $\lambda_c$ = 0.5 ft/lb$^{1/3}$ in Fig. 3.3.

The base surge produced by shallow charges (scaled depth less than 0.2 ft/lb$^{1/3}$) is relatively small and difficult to distinguish from

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[4] A. B. Arons, G. A. Young, and M. L. Milligan, Further Investigation of the Base Surge, Interim Report No. 3 on NOL Project 152, NAVORD Report 2144, 1 June 1951, pp 1-15.

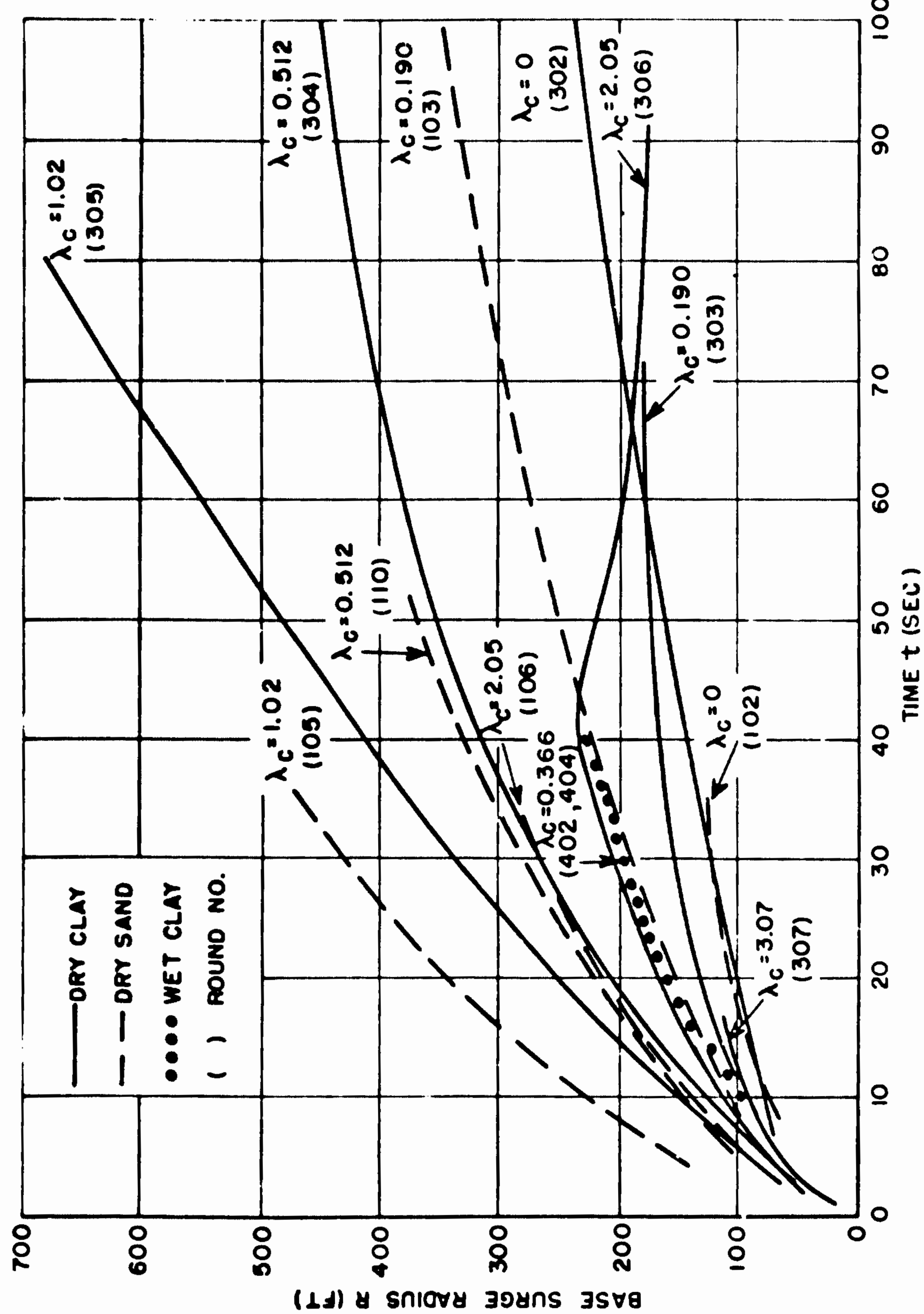


Fig. 3.1 Base Surge Radius vs Time - 320 Lb TNT Charges

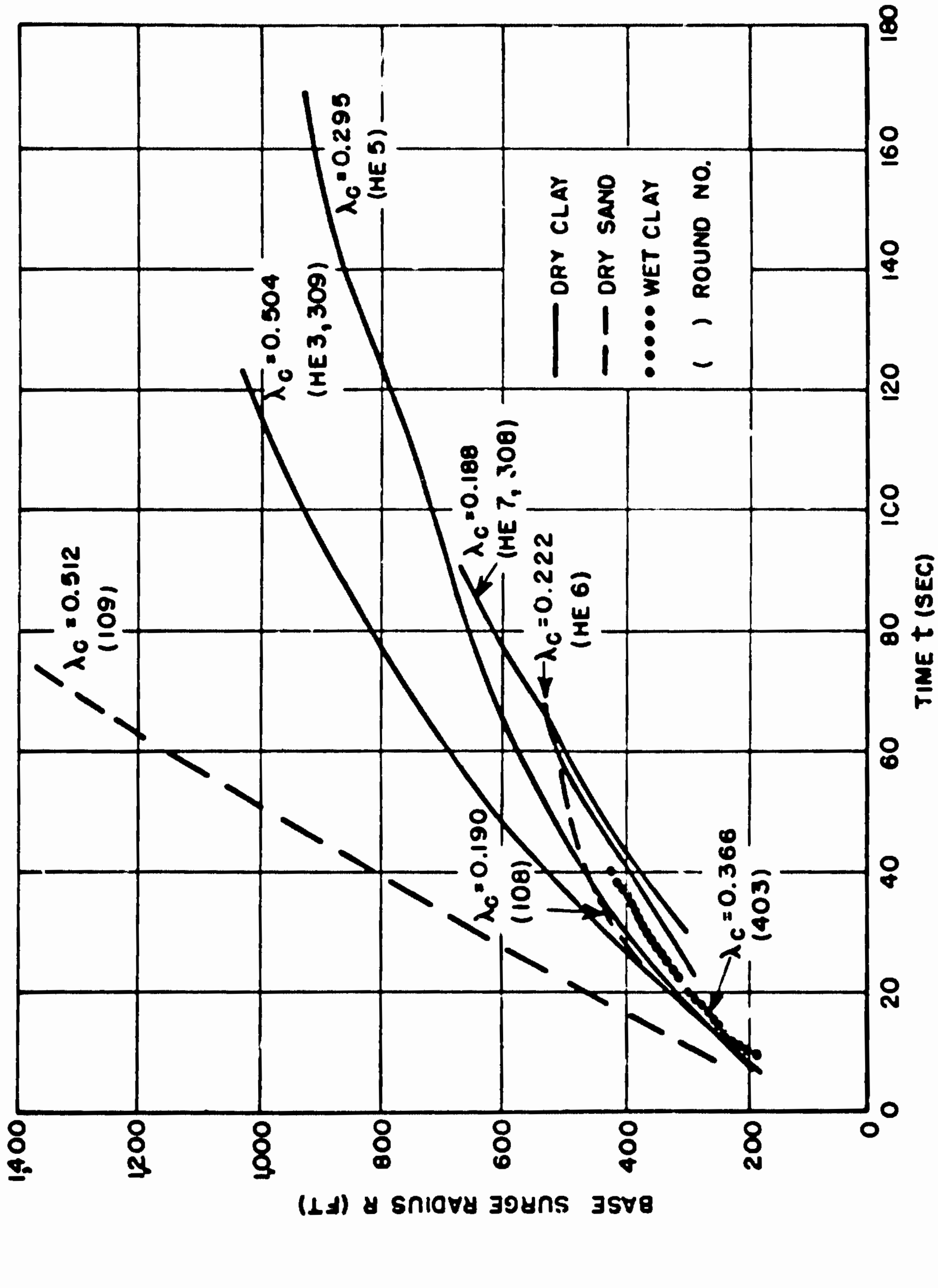


Fig. 3.2 Base Surge Radius vs Time - 2,560 Lb TNT Charges

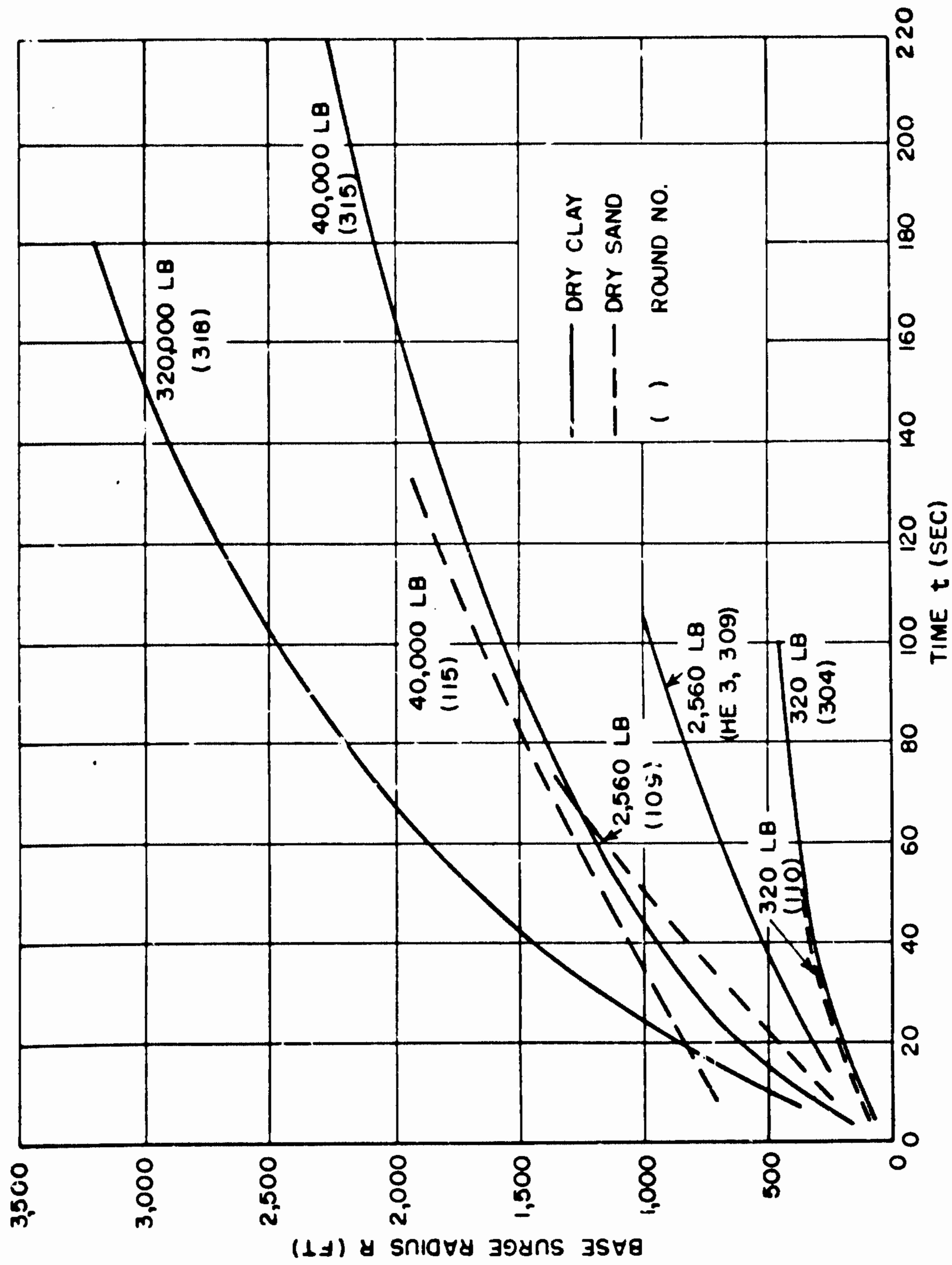


Fig. 3.3 Base Surge Radius vs Time - Scaled Depth = 0.5 $Ft/Lb^{1/3}$ (TNT)

surface dust. It is usually tenuous and has a limited radial growth. The low initial velocity and general appearance indicate that the surge density must be almost equal to that of the surrounding air at zero scaled depth. It is most probable that no recognizable surge would occur when more than half of a charge is exposed to the air at detonation.

The base surge produced by relatively deep charges (scaled depth greater than 2.5 $ft/lb^{1/3}$) is also small, but the high initial rate of spread indicates a pronounced density difference between the surge and surrounding air. The surge clouds are clearly defined, though small in size, at these depths.

In almost every case, charges fired in dry sand produced a larger, faster-moving base surge than the equivalent charges fired in dry clay. The limited data indicate that wet clay is the least effective of the three soil types for the production of a base surge.

The ends of the radius-time curves do not generally indicate the maximum radial extent of the surge cloud, but represent the limit of the available data. No objective measurement of maximum size can be made because the surge cloud grows by mixing with the surrounding air until the concentration has been reduced to a level at which the cloud is no longer visible. In cases where the growth curve indicates expansion to a maximum radius followed by a decrease in size (e.g., Round 306), the surge cloud has thinned and lifted, changing to a tall cylindrical dust cloud.

Examples of the base surge from shallow and deep charges in dry clay are shown in Figs. 3.4 and 3.5. Some dry sand and wet clay surges are presented in Figs. 3.6 and 3.7.

Surge heights are difficult to determine because of the billowy nature of the upper surface. Sometimes great differences in height occur between parts of the base surge, probably due to the lack of symmetry of the initial breakthrough of explosion gases and the subsequent irregular fallout. Theory indicates that the upper surface of a density current, such as the base surge, is subject to the formation of waves which may become unstable and lead to mixing with the air above.[5] In a dense current of this type, mixing is generally at a minimum at the leading edge. Mean values of surge height for each round are used in this presentation, but the data are subject to considerably more scatter than the measurements of surge radius.

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[5] J. S. Coles and G. A. Young, Investigations of Base Surge Phenomena by Means of High Explosives and a Liquid Model, Interim Report No. 2 of NOL Project 152, NAVORD Report 1744, 1 Sept. 1950, p 53.

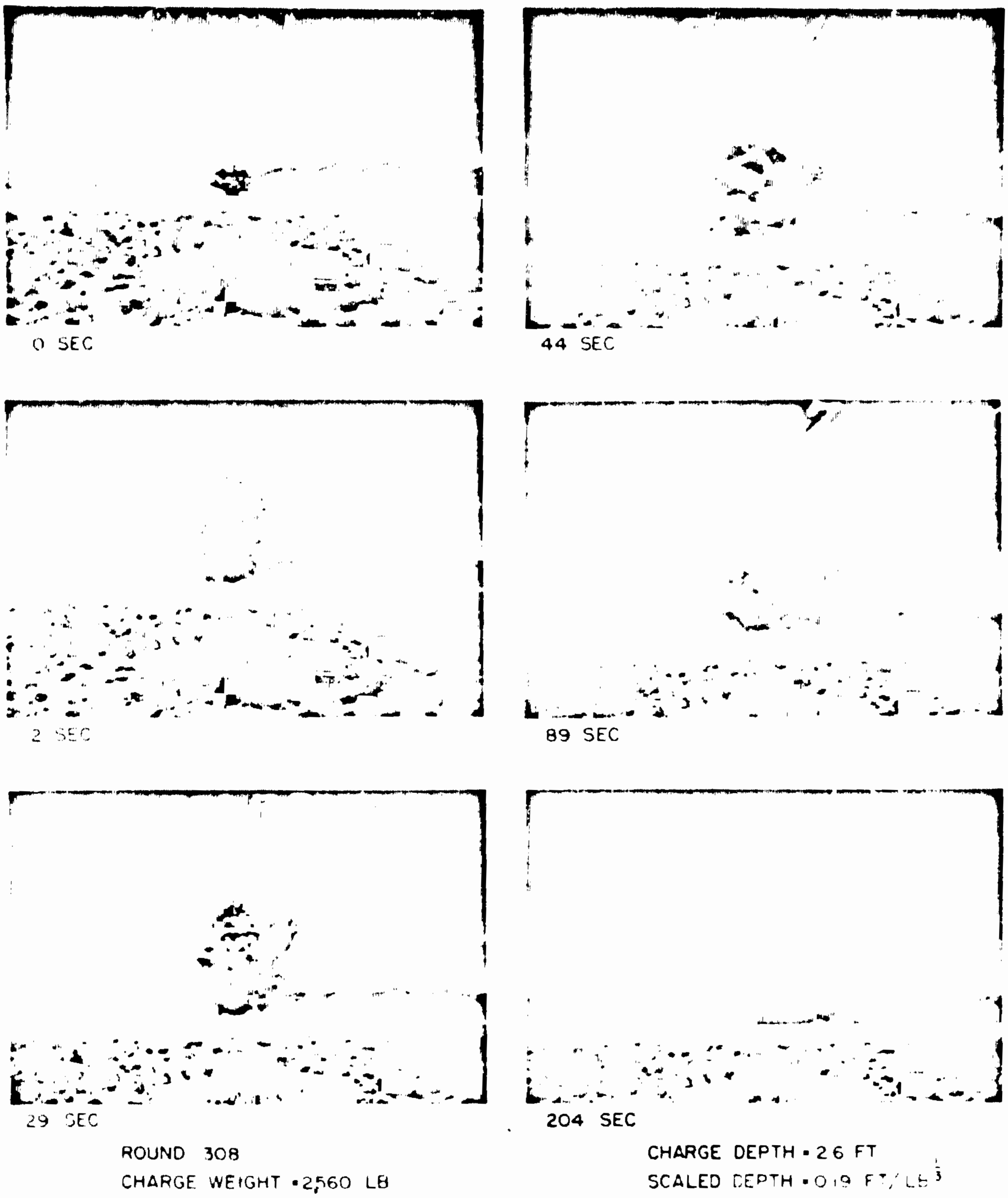


Fig. 3.4 Formation of Base Surge by Shallow Explosion in Dry Clay

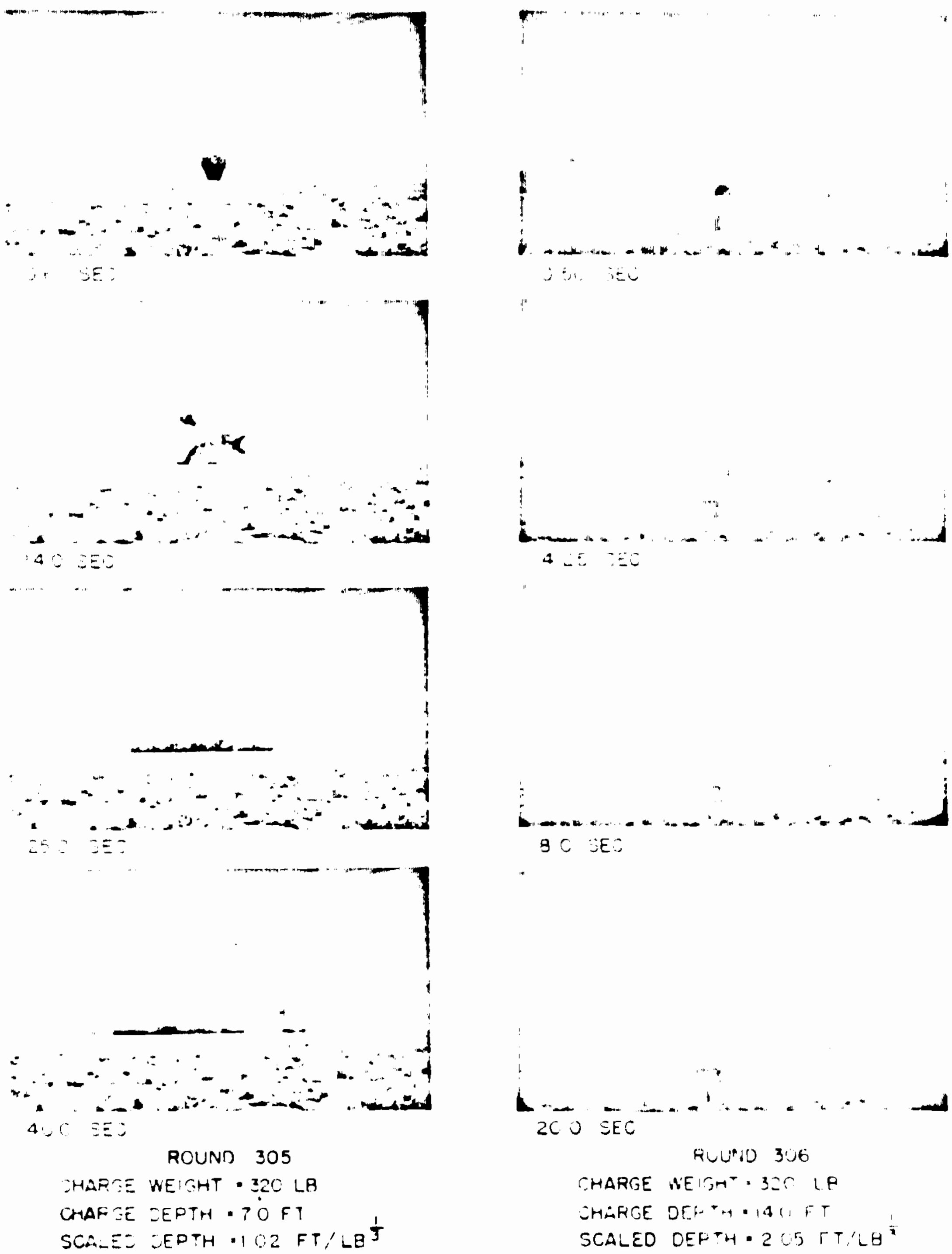


**Fig. 3.5 Formation of Base Surge by Deep Explosions in Dry Clay**

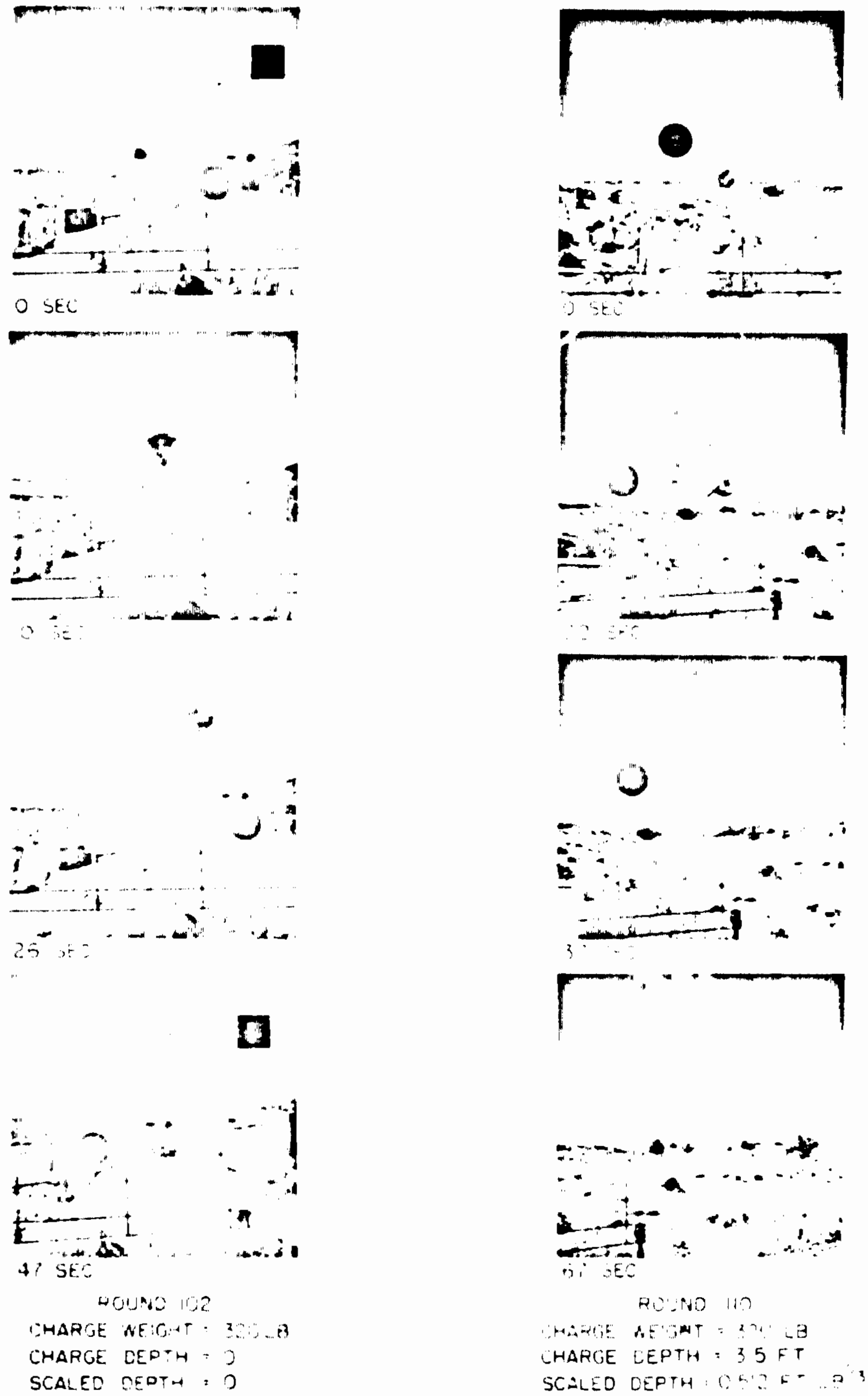


Fig. 3.6 Formation of Base Surge by Explosions in Dry Sand

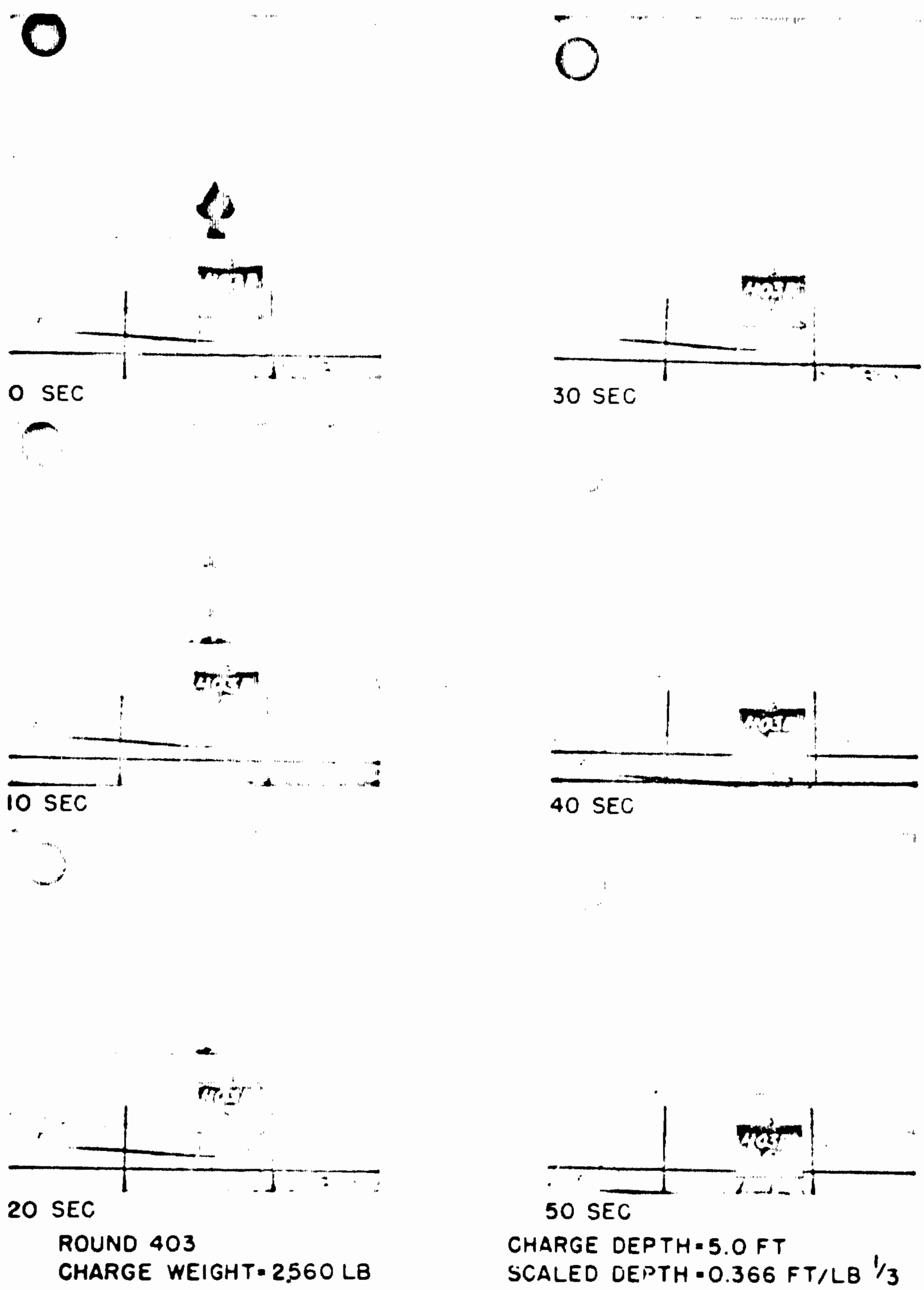


Fig. 3.7 Formation of Base Surge by Explosion in Wet Clay

The height-time curves for the base surge at different firing conditions are given in Figs. 3.8, 3.9, and 3.10. The surge cloud is shallowest during the first stage of its growth with very shallow and very deep charges, and appears to be highest for charges fired at a scaled depth of 1.02 ft/lb$^{1/3}$. The irregular growth that follows shows the effect of turbulent mixing, and the height attained before the surge dissipates is apparently independent of depth for charges of the same weight. In all cases, the surge cloud continues to rise as it expands.

The surges produced in dry sand tend to be consistently higher than surges in dry clay, but the wet clay records are not adequate to show a significant tendency. The relatively smooth appearance of the dry sand growth curves is probably not representative of the actual growth process, but is due to the large time interval between data points.

## 3.3 EFFECTS OF WIND

Wind conditions may affect the base surge indirectly by altering the rates of growth and fall of the jet. As shown in Fig. 3.11, the jet produced in a strong gusty wind by Round 312 dropped fast and caused a rapid growth of the base surge. With the same charge weight and depth, the jet from Round 309 rose into a relatively light wind and fell slowly, while the base surge expanded at a moderate rate of speed.

Aside from jet effects, the wind shortens the diameter of the surge cloud in a direction parallel to the wind direction so that the surge becomes ovoid before moving bodily downwind. When the surge is completely formed it is shaped like an irregular torus, with the downwind edge much higher than the trailing upwind side.

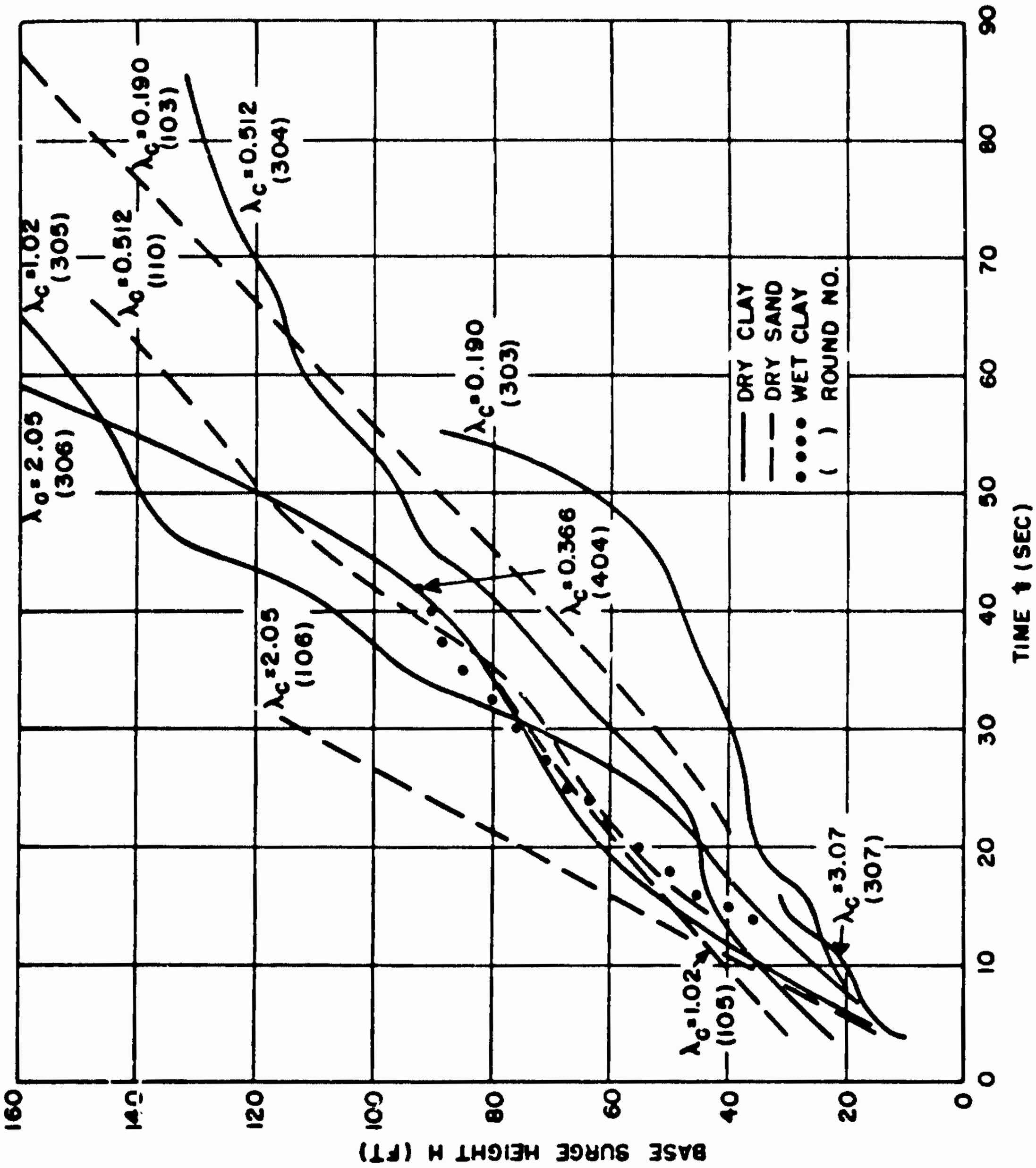


Fig. 3.8 Base Surge Height vs Time - 320 Lb TNT Charges

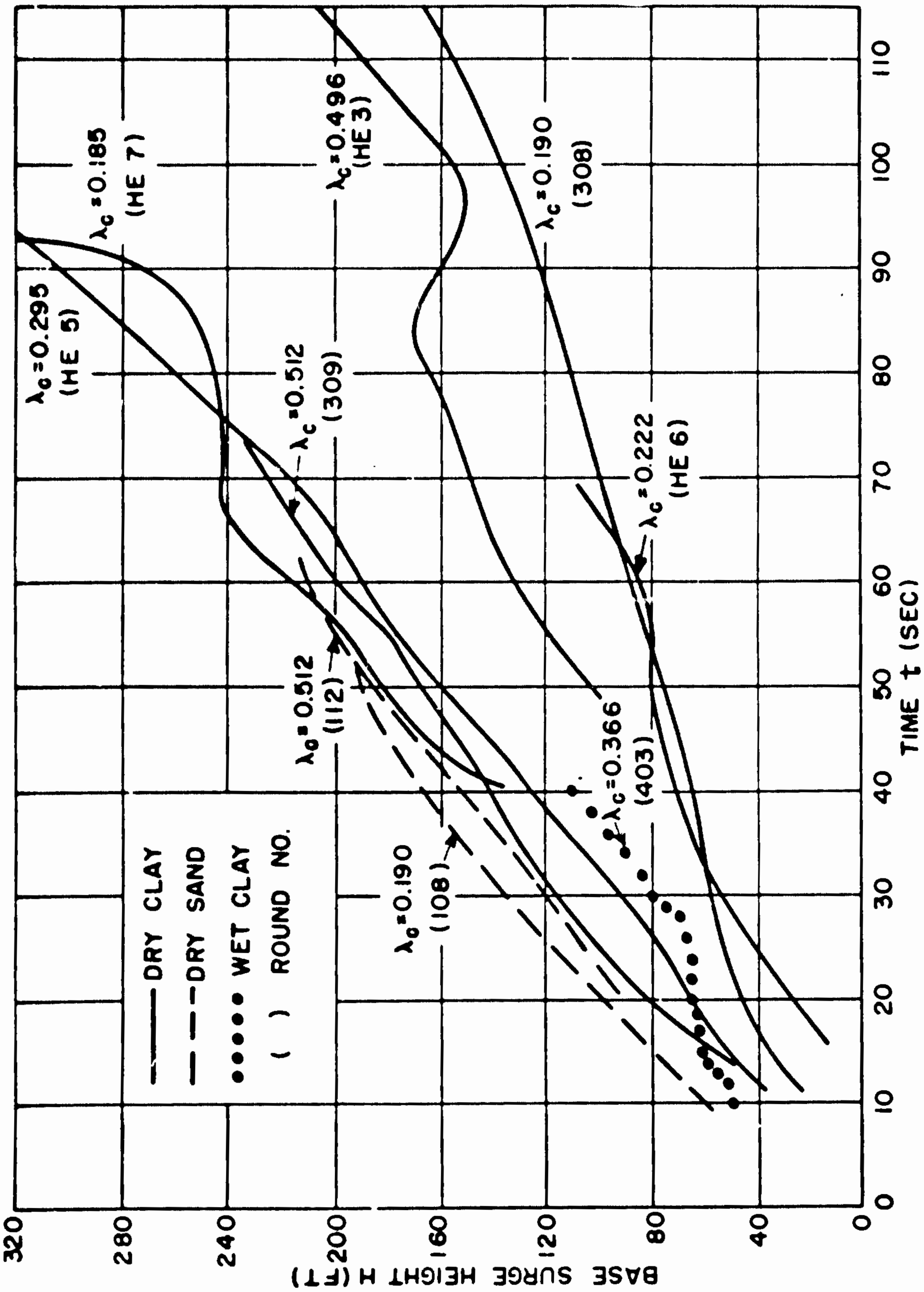


Fig. 3.9 Base Surge Height vs Time - 2,560 Lb TNT Charges

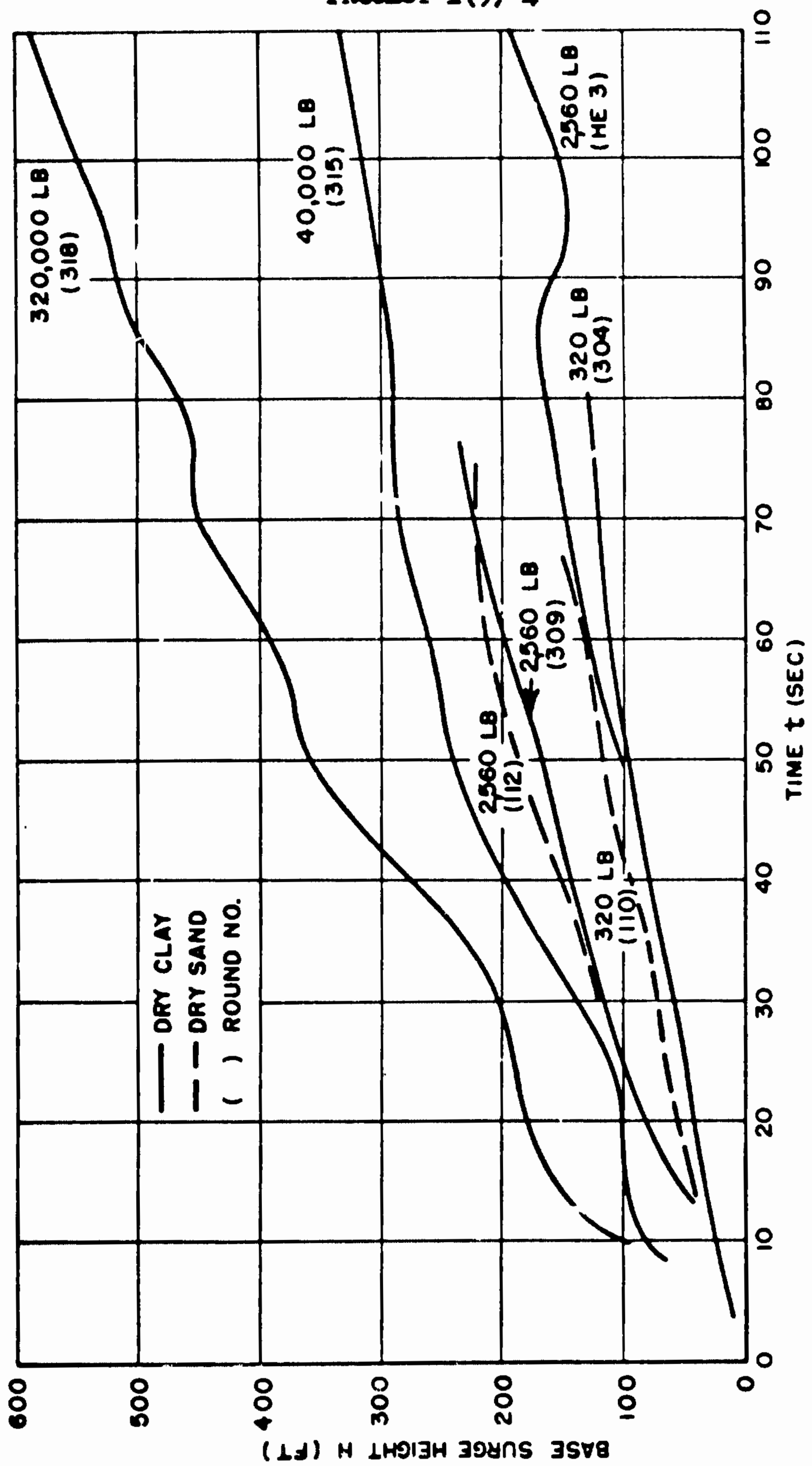


Fig. 3.10 Base Surge Height vs Time - Scaled Depth = 0.5 Ft/Lb$^{1/3}$ (TNT)

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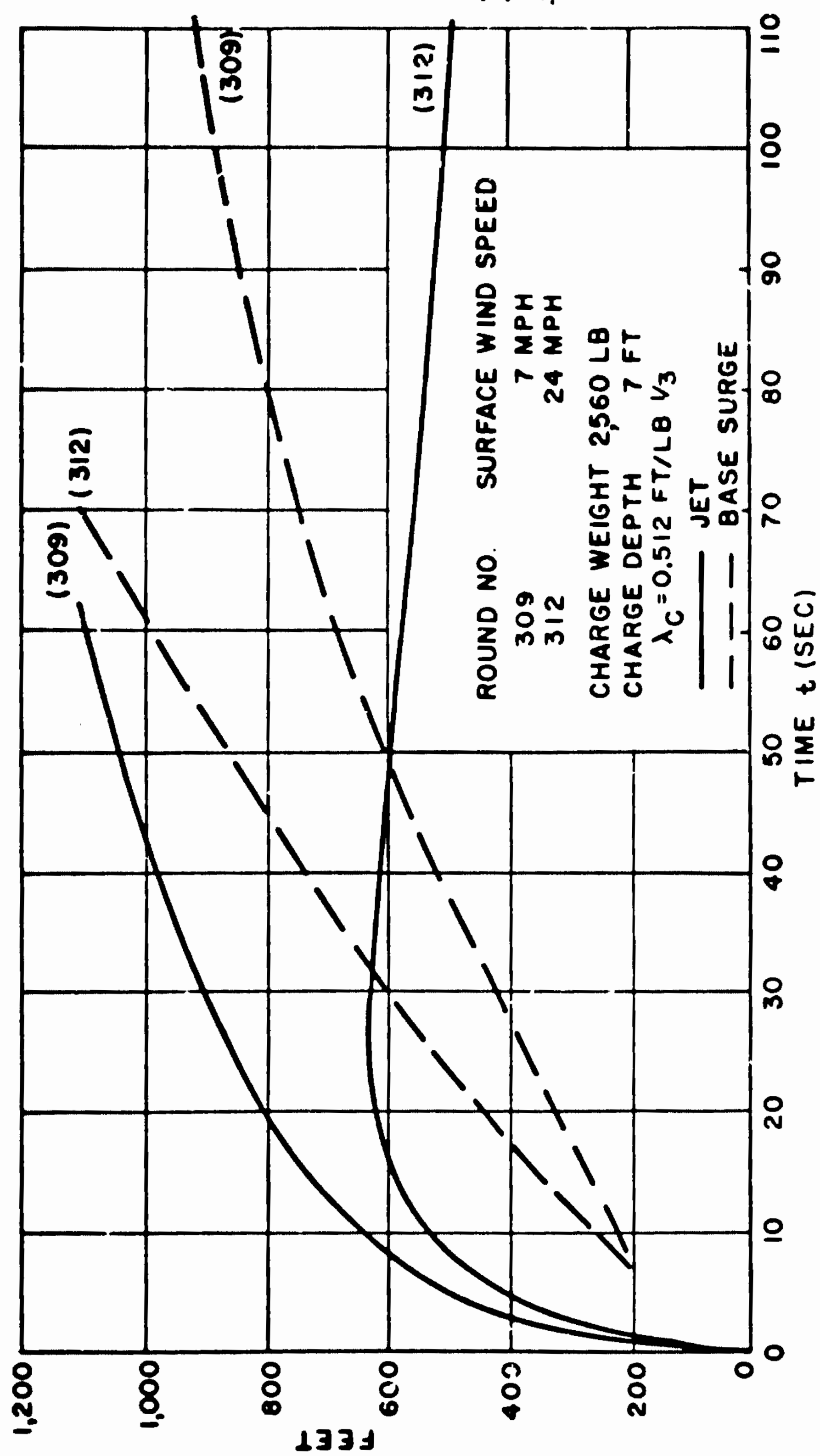


Fig. 3.11 Effect of Wind Speed on Jet and Base Surge

# CHAPTER 4

## SCALING METHODS

### 4.1 MODELS

The concept of the bulk subsidence and radial outflow of the aerosol that constitutes the base surge implies that the suspension of dust particles in air can be treated as a fluid, somewhat heavier than air. Consequently it is possible to use some of the techniques of fluid dynamics and apply the laws of similarity to the flow phenomena produced by underground explosions.

The concepts of similarity and models may be applied to base surge phenomena in two possible ways. If complete similarity exists between the surge flow produced by charges of different weights fired at the same scaled depths, the effects of large charges may be predicted by applying appropriate scaling rules to small charge results. Secondly, a better understanding of surge phenomena in general can be obtained if it is possible to simulate the base surge on a laboratory scale with dense liquids or aerosols.

A liquid model has been used with success in the study of the base surges produced by underwater explosions.[1] The model consists of a metal cylinder retaining a column of dense colored solution in the center of a tank of water. When the cylinder is removed suddenly the column descends vertically and flows outward horizontally along the bottom of the tank. Both homogeneous and hollow columns were studied, and the inner and outer diameters, column height, and fluid density were varied.

### 4.2 FROUDE SCALING OF BASE SURGE RADIAL GROWTH

As equivalence of Froude numbers is a necessary condition for similarity in all cases of flow with a free surface, Froude scaling was used for the initial flow of the surge both in the liquid model and in underwater explosions. It proved to be adequate for comparing the initial rates of growth, indicating that gravitational and inertial forces play the dominant role in establishing the character of the flow. It is

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[1] A. B. Arons, Experimental Investigations of Base Surge Phenomena, Interim Report No. 1 of NOL Project 152, NAVORD Report 1501, 13 July 1950, pp 6-7.

significant that the explosion results give best agreement with the hollow core liquid models.

A. B. Arons[2] has derived scaling laws for the initial radial propagation velocity of the surge front, obtaining the following parameters:

$$r = \frac{R}{D_{max}} \tag{4.1}$$

$$\tau = \frac{t}{D_{max}^{1/2}} \tag{4.2}$$

where
$r$ = scaled surge radius (dimensionless)
$R$ = surge radius, ft
$D_{max}$ = maximum column diameter, ft
$\tau$ = scaled time, sec/ft$^{1/2}$
$t$ = time, sec

The maximum diameter of the column is used as the characteristic length for scaling purposes. Reducing lengths by the first power of $D_{max}$ and time by the square root of $D_{max}$, as indicated above, corresponds to Froude scaling. If this procedure is adequate, measurements of the radial growth of the base surge produced by charges fired at the same scaled depth should lie on the same curve when scaled in this manner.

For complete geometrical similarity, the ratios between corresponding lengths in model and prototype should be the same. Therefore, the effective column height and the diameter of the core must be directly proportional to maximum column diameter for this method to be applicable. This proved to be true in the study of underwater explosions, and good agreement was obtained between the scaled surge radius vs scaled time curve for Test Baker at Bikini and the curves obtained from high explosives fired at the same or similar scaled depths, out to about $\tau = 1.5$ sec/ft$^{1/2}$.

The radial growth of the base surges produced by underground explosions in the Dugway dry clay tests and in the Nevada HE program is shown in Fig. 4.1, reduced according to the same Froude scaling parameters.

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[2] Ibid., pp 2-3.

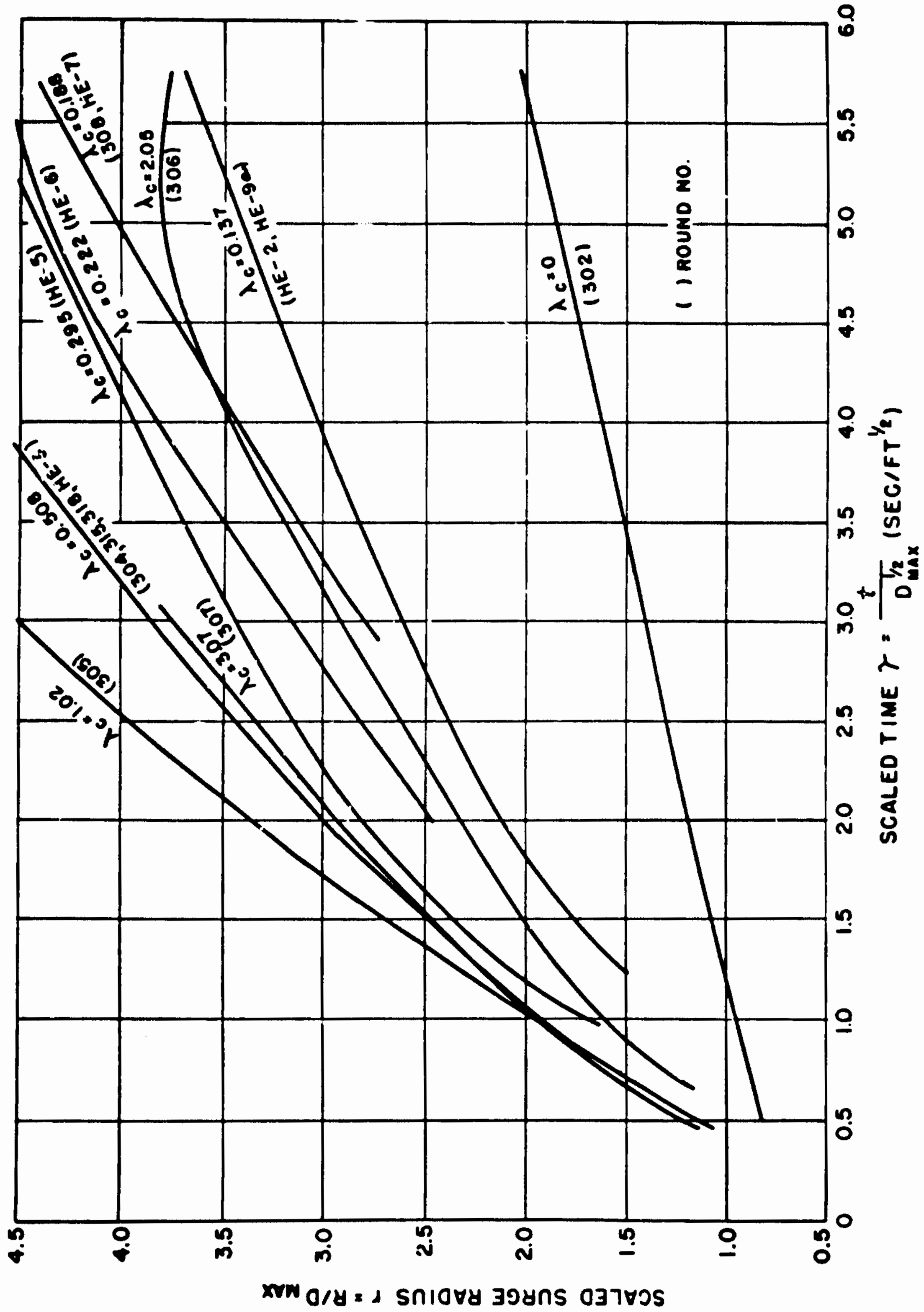


Fig. 4.1 Preliminary Scaling of Radial Growth of Base Surge in Dry Clay

Where available, data for different rounds fired at the same scaled depths were averaged. As the ratio of maximum column height to maximum column diameter is the same (see Section 2.4) for charges fired at the same scaled depth in the same type of soil, the corresponding scaled surge radius vs scaled time curves are similar. Thus it appears that the diameter of the core of the column is directly proportional to the outer diameter for all charges fired at the same scaled depth in the same soil.

Figure 4.1 shows a gradual increase of scaled radial surge growth with increasing values of $\lambda_c$ to a maximum at 1.02 ft/lb$^{1/3}$, with lower values at greater scaled depths. This is consistent with the measurements of $C_{max}$ in indicating a high initial velocity for the tallest columns. The later portions of the curves show atmospheric effects.

The reason for the apparent inconsistency of the record for Round 307 ($\lambda_c$ = 3.07 ft/lb$^{1/3}$) is not known, but may be due to differences between the internal structure of the column and the structure of the columns produced by shallower charges.

As the above scaling procedure is not complete, Arons[3] has derived more generalized Froude scaling criteria, defining scaled radius as before and scaled time in the following manner:

$$\tau^* = \frac{t\ (\sigma C_{max})^{1/2}}{D_{max}} \qquad (4.3)$$

where $\tau^*$ = scaled time, sec/ft$^{1/2}$

$$\sigma = \frac{\rho - \rho_0}{\rho}$$

$\rho$ = density of moving fluid
$\rho_0$ = density of ambient fluid
$C_{max}$ = maximum column height, ft
$D_{max}$ = maximum column diameter, ft

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[3] A. B. Arons, G. A. Young, and M. L. Milligan, Further Investigation of the Base Surge, Interim Report No. 3 of NOL Project 152, NAVORD Report 2144, 1 June 1951, pp 4-5.

This more complete scaling does not provide for hollow columns but permits the comparison of records when density ratios and column heights are varied. However, measurements of radial surge growth when reduced in the form of r vs $\tau^*$, should fall on a single curve for all tests with the same ratio of core to outer column diameter.

The modified scaling law does not take into account all of the physical effects of differences between the densities of the moving and ambient fluids. However, when applied to liquid model results, it proved extremely useful in the study of the simulated base surge.[4] The resulting scaled curves are reproduced in Fig. 4.2 and show the following:

(a) For any given $\sigma$ and ratio of core to column diameter ($D_c/D$) there is a separate r vs $\tau^*$ curve embracing the effects of variation of $C_{max}$ and $D_{max}$.

(b) The r vs $\tau^*$ curves show a lower slope with decreasing $\rho$ (or $\sigma$) and increasing $D_c/D$.

(c) The slope is more sensitive to density changes of a fixed value in the lower density region.

The following relation between $\tau$ and $\tau^*$ can be obtained:

$$\tau^* = \tau \left( \frac{\sigma C_{max}}{D_{max}} \right)^{1/2} \tag{4.4}$$

It is also convenient to define a scaled time parameter, which does not include a density term, as follows:

$$\tau' = \tau \left( \frac{C_{max}}{D_{max}} \right)^{1/2} \tag{4.5}$$

In the scaling of underwater explosion results, the r vs $\tau$ data for the initial portion of the Bikini base surge flow was computed, and the values of $\tau$ were multiplied by various assumed values of $(\sigma C_{max}/D_{max})^{1/2}$. The resulting curves were compared with similarly scaled liquid model curves and the agreement of slopes proved best

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[4] Ibid., pp 5-8.

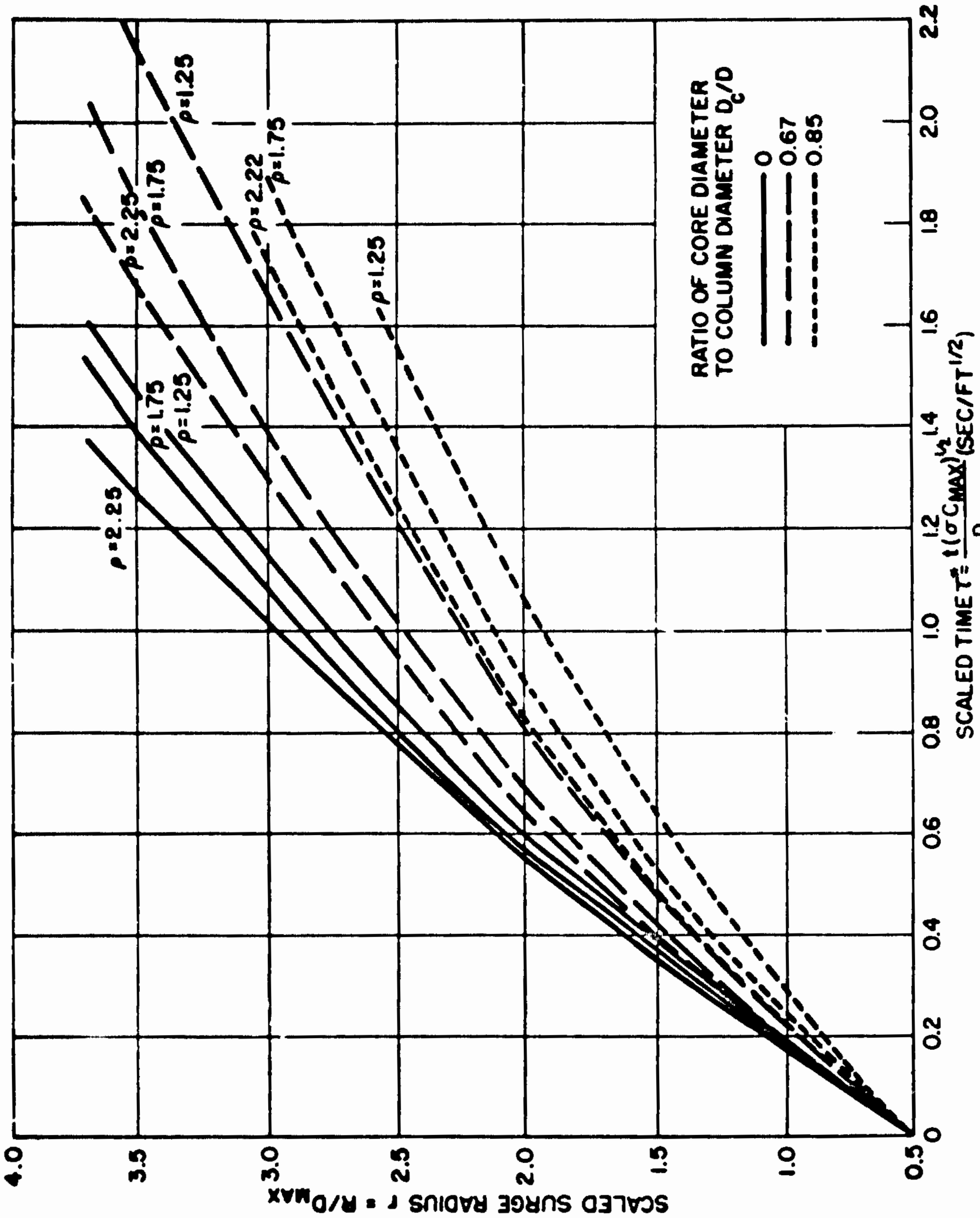


Fig. 4.2 Scaled Liquid Model Results

with liquid models having a water core ratio of about 0.7. The appropriate value of $(\sigma C_{max}/D_{max})^{1/2}$ lay somewhere between 0.77 and 0.88. Since $D^{1/2}$ was equal to 45.1 for Test Baker, the corresponding values of $(\sigma C)^{1/2}$ for the Baker column were between 35 and 39. This permitted a calculation of the probable range of density and height of the Baker column, and the estimate was made that the ratio of column density to ambient density was about 1.5, with an effective column height of about 4000 ft and a core ratio of about 0.7.[5]

As the values of maximum column height are known for the underground explosion data plotted in Fig. 4.1, a first step toward a more complete scaling is the multiplication of the known values of $\tau$ by the square root of the ratio of $C_{max}$ to $D_{max}$ for each scaled depth. (See Fig. 2.8.) As the measured ratio for Round HE-6 ($\lambda_c$ = 0.222) appeared to be doubtful, a value of 0.685 was obtained from the smoothed curve and substituted for the recorded ratio. The resulting r vs $\tau'$ curves are shown in Fig. 4.3.

The separation in these partially scaled curves should be due only to differences in $D_c/D$ and the bulk density of the material in the column that forms the base surge. Neither of these quantities has been measured, but if one could be determined it might be possible to estimate the magnitude of the other, for a particular scaled depth.

If the assumption is made that the diameter of the core is equal to the true crater diameter, it is possible to estimate the ratio of core to outer column diameter ($D_c/D$) for the rounds used to obtain the curves shown in Figs. 4.1 and 4.3. The mean values of the ratios of true crater diameter to maximum column diameter given in Fig. 6.3 are generally intermediate between the values of $D_c/D$ for which liquid model results are available. As the crater-column ratio is equal to 0.46 for charges scaled to 0.508 ft/lb$^{1/3}$, interpolated liquid model curves for $D_c/D$ = 0.46 are presented in Fig. 4.4 for comparison with the scaled explosion surge curves.

If column heights, column diameters, core diameters, and ratios between the densities of the earth columns and the surrounding air were known accurately, the scaled curves for explosion base surge growth would be identical with scaled curves obtained from geometrically similar liquid models with the same ratios between column and ambient densities, providing that the use of Froude scaling is valid.

This ideal situation does not exist, and many simplifying assumptions have been made, but by applying the trial-and-error process of assuming

[5] Ibid., pp 12-13.

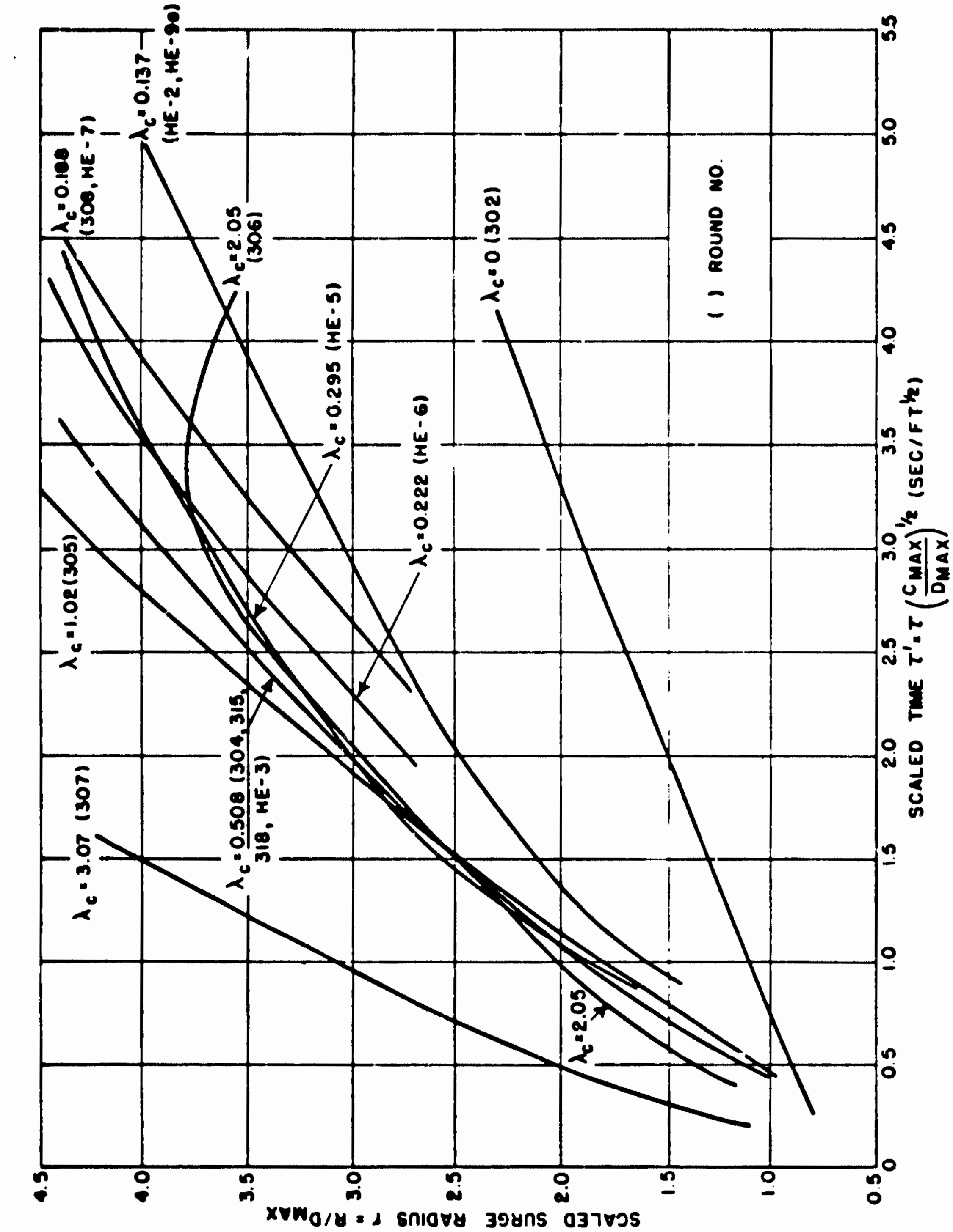


Fig. 4.3 Scaling of Radial Growth of Base Surge in Dry Clay with Column Height Effect Included

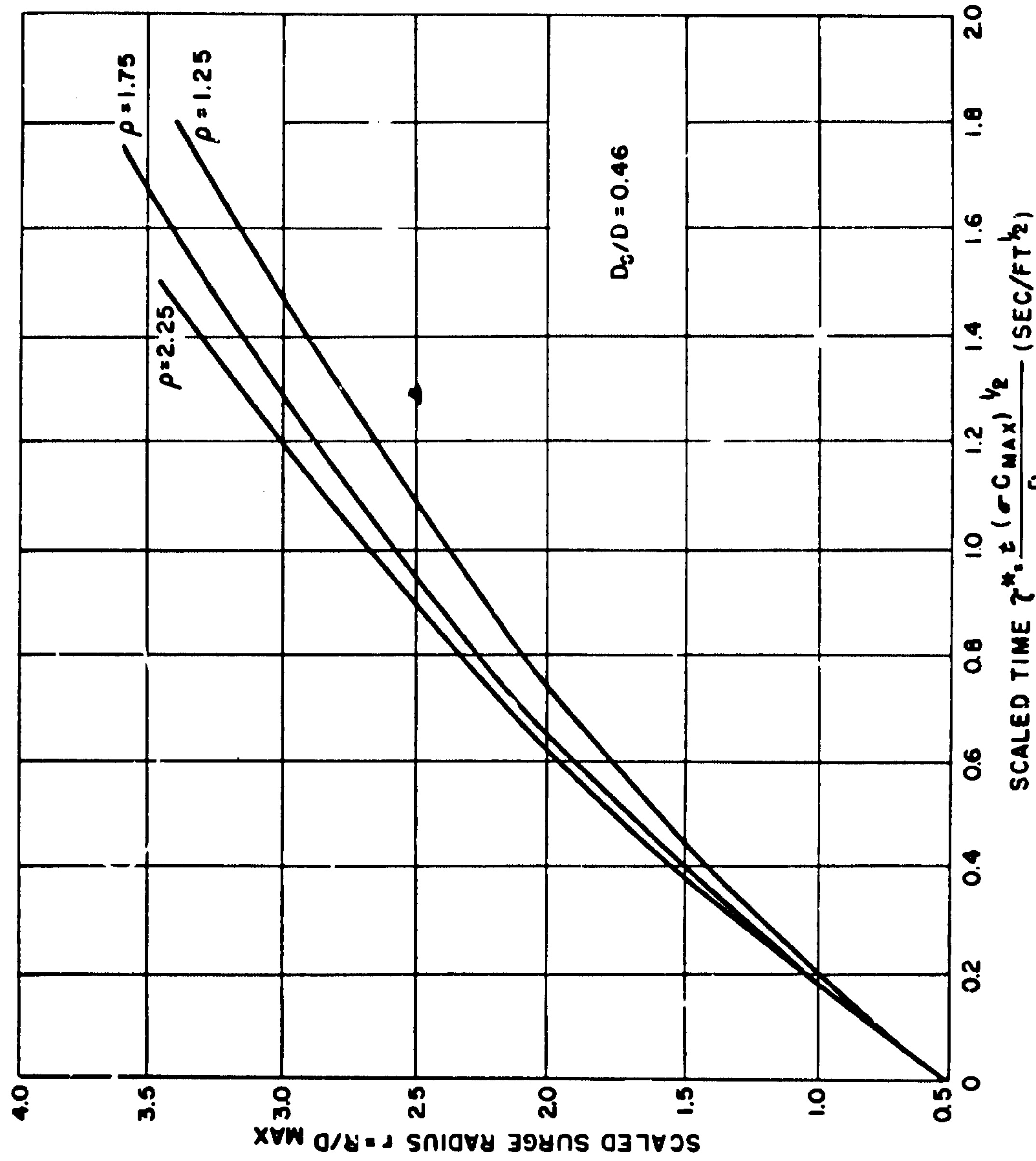


Fig. 4.4 Interpolated Scaled Liquid Model Curves for a 0.46 Ratio of Core Diameter to Column Diameter

different density values for the earth columns and multiplying the values of $\tau'$ in Fig. 4.3 by the computed values of $\sigma^{1/2}$ it is possible to obtain r vs $\tau^*$ curves for the explosions to compare with the liquid model curves. As the origin of time for the liquid model curves in Figs. 4.2 and 4.4 is the instant at which the surge emerges from the base of the column, the partially scaled curves in Fig. 4.3 should be extrapolated to find the time at which the scaled surge radius is equal to 0.5 and this time used as the actual origin for $\tau^*$.

The corrected scaled curve for a scaled depth of 0.508 ft/lb$^{1/3}$ is given in Fig. 4.5 with derived curves for several possible values of column specific gravity. The most consistent agreement between curves with the same density ratio in liquid model and prototype occurs with an assumed $\rho/\rho_0$ of about 1.9. This would indicate that the aerosol in the earth column which contributes to the formation of the base surge has about 1.9 times the density of the surrounding air, when high explosive charges are fired at a scaled depth of about 0.5 ft/lb$^{1/3}$.

The mean scaled radius vs scaled time data for this value of $\lambda_c$ was obtained from measurements of Rounds 304, HE-3, 315, and 318. Atmospheric density was computed for the time of firing of these rounds, using meteorological data obtained at Dugway[6] and Nevada,[7] and was found to be 0.0657, 0.0632, 0.0645, and 0.0632 lb/cu ft respectively. In accordance with the density ratio of 1.9 obtained from the comparison of scaled curves, the bulk densities of the aerosols in the columns were approximately 0.125, 0.120, 0.123, and 0.120 lb/cu ft. Using mean densities of 0.122 lb/cu ft for columns and 0.0642 lb/cu ft for the atmosphere, and the column dimensions presented previously, it is possible to compute the approximate weight of finely divided soil in the columns formed by these rounds that produced the base surge. These values are listed in Table 4.1.

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6 Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 1, Dry Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Aug. 1951, pp 4-9 to 4-85.

7 D. C. Campbell, LCDR, USN, Tests and Observations on Craters and Base Surges, JANGLE Report 1(9)-3, 1 Nov. 1951.

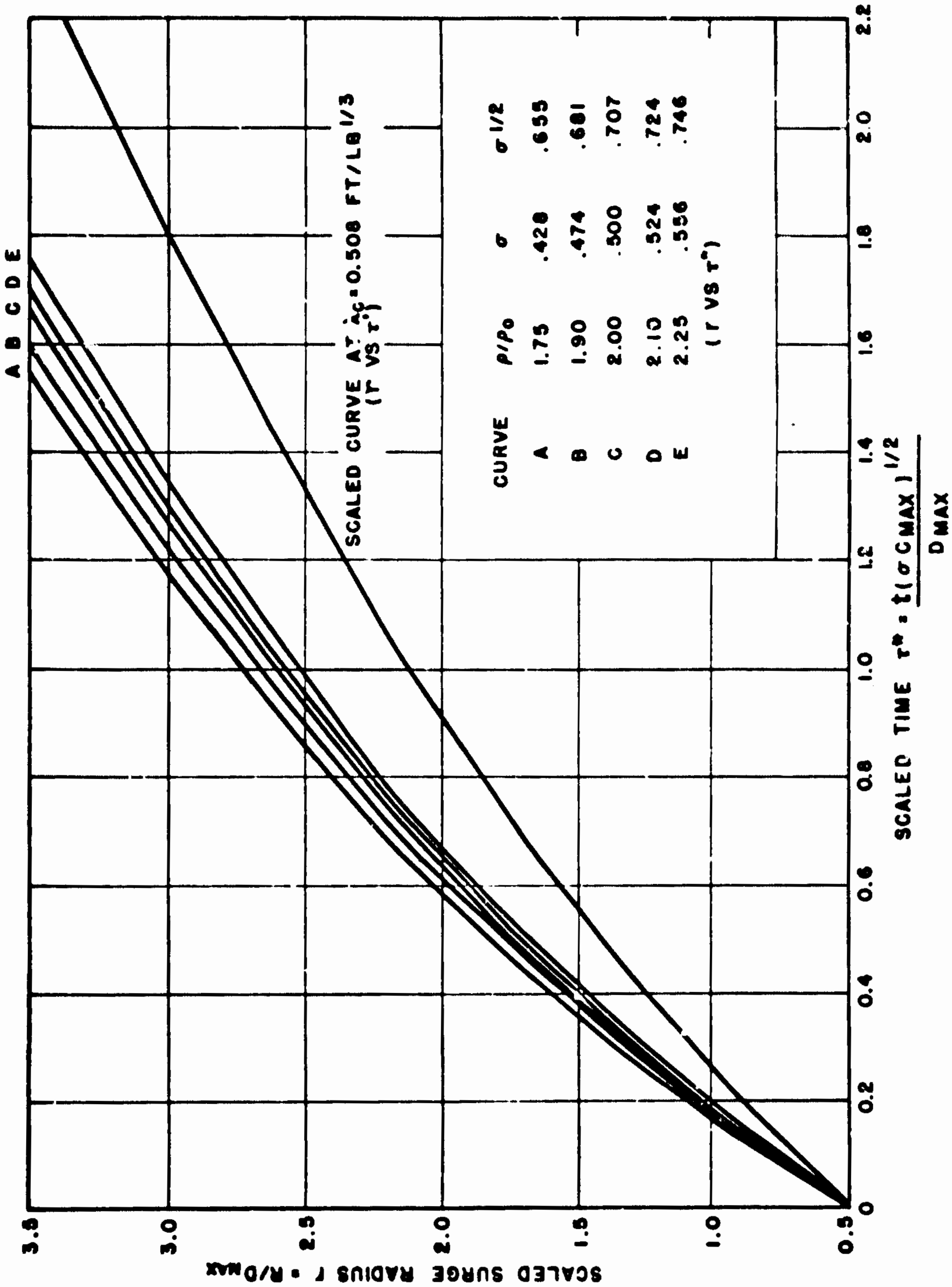


Fig. 4.5 Scaled Radial Growth of Base Surge in Dry Clay at Scaled Depth of 0.508 Ft/Lb$^{1/3}$ With Assumed Values of Column Density

TABLE 4.1

Estimated Weights of Soil in Base Surges for Rounds Fired at a Scaled Depth of 0.5 ft/lb$^{1/3}$

| Round | Charge Weight (lb TNT) | Soil Weight (lb) |
|---|---|---|
| 304 | 320 | 8,950 |
| HE-3 | 2,560 | 53,400 |
| 315 | 40,000 | 529,000 |
| 318 | 320,000 | 2,980,000 |

The relation between weight of soil in the column aerosols produced by charges fired at $\lambda_c = 0.5$ ft/lb$^{1/3}$ and charge weight may be expressed in the following manner:

$$S = 77.4\, W^{0.833} \quad (\lambda_c = 0.5 \text{ ft/lb}^{1/3}) \qquad (4.6)$$

where S = weight of soil that forms the base surge, lb
W = charge weight, lb (TNT)

The scaled curves for $\lambda_c = 1.02$ and 0.295 ft/lb$^{1/3}$ given in Fig. 4.3 are similar to the curve for $\lambda_c = 0.508$ ft/lb$^{1/3}$ to a scaled surge radius of about 3.0, and the ratios of true crater diameter to maximum column diameter are not greatly different. Therefore the ratio of the bulk density of the column aerosols to atmospheric density for charges at these scaled depths is probably approximately equal to 2.0 also. In view of the scarcity of data at these scaled depths and the assumptions necessary in the application of the scaling method, an attempt to compute the density ratio more closely would not be justified.

The shapes of the curves and probable values of D /D indicate that the column and initial surge density increase with increasing charge depth. The inconsistency of the scaled curve at $\lambda_c = 3.07$ ft/lb$^{1/3}$ indicates that this scaling method is not applicable at relatively great depths, without additional knowledge of column structure.

The rapid decrease in the slope of the scaled curve for a $\lambda_c$ value of 0.137 ft/lb$^{1/3}$ in Fig. 4.3 indicates that frictional drag becomes effective very soon after the base surge forms at this scaled depth. A

more elaborate scaling technique would be required to study this type of flow.

The relatively straight curve for $\lambda_c$ = zero shows that the gravity flow is relatively brief and ineffective and that almost all of the growth of the surge cloud at this shallow position is probably due to turbulent mixing with the surrounding air.

## 4.3 SIMILARITY TO UNDERWATER RESULTS

It is of interest to note that the r vs $\tau$ curves for underground explosions at $\lambda_c = 0.508$ agree very closely with the scaled curve for the growth of the base surge produced by the underwater atomic test (Baker) at Bikini out to about r = 2.0. The base surge formed by the underwater atomic explosion expanded at a relatively slower rate from there on.

Arons' estimate of a column density of 1.5 times the density of the surrounding air for Test Baker and the estimate by Martin and Moyce[8] of a $\rho/\rho_0$ of 1.75 for the same test are not significantly different from the $\rho/\rho_0$ value of 1.9 calculated for the soil columns produced at a scaled depth of 0.508 $ft/lb^{1/3}$.

These results indicate a similarity between the physical processes of base surge formation by underwater and underground explosions and show that liquid model experiments can be used successfully in the study of both types. Thus, theoretical and experimental results obtained in the investigation of one form of surge will be of value in the study of analogous phases of the other.

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[8] J. C. Martin and W. J. Moyce, "An Experimental Study of the Collapse of Fluid Columns on a Rigid Horizontal Plane, in a Medium of Lower, but Comparable, Density", Philosophical Transactions of the Royal Society of London, Series A, No. 882, Vol 244, 4 March 1952, p 333.

# CHAPTER 5

## AREA OF DUST DEPOSIT

### 5.1 ANALYSIS OF DATA

The Armour Research Foundation of the Illinois Institute of Technology investigated the dispersion of dust from underground explosions at Dugway under subcontract to Engineering Research Associates, Inc.[1] As part of the instrumental program, settlement gages were placed at a number of points surrounding the explosion sites, in order to obtain a record of dust-fall distribution by weight. Polar graphs of settlement data were presented in Interim Technical Reports No. 1,[2] 2,[3] and 3[4] showing lines of constant dust-fall weights around the point of the explosion for three types of soil. The lines represent values of 0.5, 1.0, 5.0, 10, 50, 100, 500, 1000, 3000 and 6000 grams per square meter.

In most cases the graphs showed a roughly circular dust distribution around the crater with a tongue of deposited dust extending downwind. Considerable smoothing and extrapolation were necessary in the preparation of the charts; and the size and shape of the areas of dust fall and the uniformity of dust coverage were greatly affected by wind and atmospheric turbulence. Because of these effects, the data presented are subject to considerable scatter and are not always comparable, but are considered adequate for showing the important trends.

Although these data represent total dust deposit from the radial throwout and all parts of the dust cloud, the maximum extent of deposit

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[1] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 1, Dry Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Aug. 1951, pp 4-1 to 4-7.

[2] Ibid., pp 4-86 to 4-108.

[3] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 2, Dry Sand, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Oct. 1951, pp 4-47 to 4-57.

[4] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 3, Wet Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Nov. 1951, pp 4-31 to 4-37.

probably coincides closely with the limit of radial surge growth along the ground, except possibly in the downwind direction when the upper winds are strong. As the determination of the absolute boundaries of dust-fall is probably impossible, particularly when a small amount of airborne dust is present, greater objectivity is attained by measuring the area containing a dust deposit equal to or greater than some fixed low value. It seems justified to assume that the area enclosed by a line of low dust-fall, such as 0.5 grams per square meter, is closely related to the size of the surge cloud. However, correlating these dust data with surge extent is not valid when the base surge is relatively small and poorly defined, as occurs with shallow charges (scaled depths less than 0.2 $ft/lb^{1/3}$).

To compare these data with the base surge analysis, the areas inside the lines representing dust deposits of 0.5 and 50 grams per square meter were measured at NOL with a planimeter, using the A.R.F. analysis. The areas obtained from the A.R.F. charts are listed in Table 5.1. Data for the 320 lb and 2560 lb charges are shown in Fig. 5.1 as a function of scaled depth ($\lambda_c$). The plotted data for the 320 lb dry clay and dry sand series are consistent with base surge growth data in showing the greatest area of deposit when $\lambda_c = 1.0$.

Charges fired in dry sand produced greater areas of dust-fall than charges fired at the same scaled depths in dry clay, and the two data points for Rounds 402 and 404 indicate that charges fired in wet clay yield the smallest areas of dust-fall. These results are consistent with base surge measurements and support the hypothesis that dry sand is the most favorable of the three Dugway soils for producing a base surge and wet clay the least.

The relatively large areas for Rounds 102 and 302 can not be considered to represent surge growth but are due chiefly to the broad dust columns of low density which fell slowly and were easily transported by the wind.

A careful analysis of data from a dense network of settlement gages should show a heavy fallout of large particles near the crater and in the downwind path of the jet and column and a more uniform light deposit in the area traversed by the surge. A complete analysis of this type is not possible with the available data, but a plot of deposit weights against area for Rounds 309 and 312 ($\lambda_c = 0.512$) on rectilinear graph paper shows a pronounced change in slope between the dust-fall values of 10 and 50 grams per square meter. Assuming that the 30 gram per square meter line marked the approximate extent of the heavy vertical fallout from the jet and column, the data show that this fallout accounted for less than 15% of the total area of deposit in both cases. At this scaled depth, the passage of the surge cloud and the gradual settlement of finer particles from the jet and smoke crown probably were responsible for over 85% of

TABLE 5.1

Areas of Dust Deposit for Dugway Underground Explosion Tests

| Round | Charge Weight (lb TNT) | Soil Type | Area of Dust-fall: $\geq$ 50 gm/sq m (sq ft) | Area of Dust-fall: $\geq$ 0.5 gm/sq m (sq ft) | Wind Speed (mph) |
|---|---|---|---|---|---|
| 302 | 320 | Dry Clay | 44,800 | 1,230,000 | 13 |
| 303 | 320 | Dry Clay | 47,900 | 386,000 | 4 |
| 304 | 320 | Dry Clay | 92,500 | 1,860,000 | 6 |
| 305 | 320 | Dry Clay | 135,000 | 2,720,000 | 7 |
| 306 | 320 | Dry Clay | 23,000 | 213,000 | 8 |
| 308 | 2,560 | Dry Clay | 500,000 | 17,200,000 | 3 |
| 309 | 2,560 | Dry Clay | --- | 38,200,000 | 7 |
| 310 | 320 | Dry Clay | 102,000 | 1,720,000 | 10 |
| 312 | 2,560 | Dry Clay | 534,000 | 13,600,000 | 24 |
| 313 | 320 | Dry Clay | 122,000 | 1,690,000 | 15 |
| 315 | 40,000 | Dry Clay | 3,980,000 | 35,100,000 | 3 |
| 318 | 320,000 | Dry Clay | 21,500,[illegible]0 | 223,000,000 | 4 |
| 102 | 320 | Dry Sand | 48,[illegible]00 | --- | 4 |
| 103 | 320 | Dry Sand | 95,800 | --- | 2 |
| 105 | 320 | Dry Sand | 229,000 | 5,250,000 | 5 |
| 106 | 320 | Dry Sand | 39,900 | 408,000 | 2 |
| 108 | 2,560 | Dry Sand | 530,000 | 16,900,000 | 11 |
| 110 | 320 | Dry Sand | 130,000 | 5,210,000 | 5 |
| 112 | 2,560 | Dry Sand | 530,000 | --- | 6 |
| 115 | 40,000 | Dry Sand | 5,960,000 | --- | 12 |
| 402 | 320 | Wet Clay | 238,000 | --- | 16 |
| 404 | 320 | Wet Clay | 200,000 | --- | 22 |

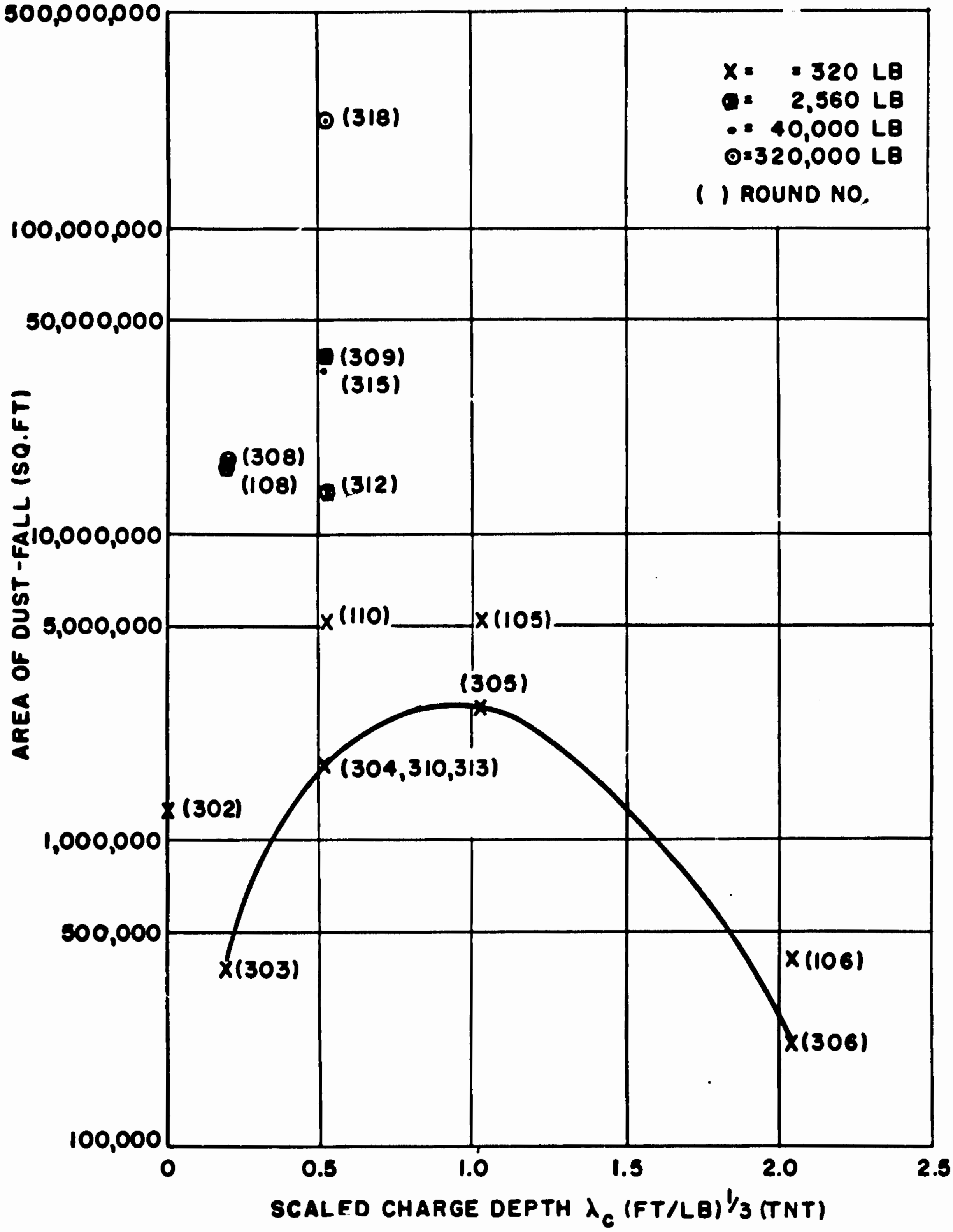


Fig. 5.1 Area of Dust-Fall = 0.5 gm/sq m vs Scaled Charge Depth

the dust-fall area.

## 5.2 METEOROLOGICAL EFFECTS

The available data are not adequate for a complete study of the effects of wind and atmospheric stability on the dispersal of the various parts of the surface phenomena and the consequent areas of dust-fall, but some purely qualitative results can be obtained.

In general, an increase in wind speed indicates a decrease in the area traversed by the surge cloud and an increase in the area of fall-out from the column. This effect is shown by the data in Table 5.1 for Rounds 304, 310, and 313 (320 lb charges at a 3.5 ft depth in dry clay; $\lambda_c = 0.512$ ft/lb$^{1/3}$), assuming that the area covered by more than 50 grams per square meter of dust is roughly indicative of the fallout region and the area between the 0.5 and 50 grams per square meter lines is representative of the base surge settlement.

The same effect appears for Rounds 309 and 312, both 2560 lb charges fired at a 7 ft depth in dry clay ($\lambda_c = 0.512$ ft/lb$^{1/3}$). Rounds 309 and 312 were fired with 7 and 24 mph surface winds respectively. For Shot 309 the line of 0.5 gram per square meter dust-fall enclosed a broad tongue extending 9430 ft downwind from the crater with a total area of 1.37 sq mi, while Shot 312 produced a relatively narrow tongue with the same dust-fall, extending 7390 ft downwind and including a total area of 0.489 sq mi. In this case the area covered by dust weighing 0.5 grams per square meter or more was about three times as great with a relatively light wind as with a strong wind. However, the area of heavy dust-fall was greater for 312 than 309, indicating a greater uniformity of deposit with the stronger wind. The distribution of dust-fall by weight for both rounds is shown in Fig. 5.2.

These results are consistent with the experience of the Chemical Warfare Service in the study of the behavior of clouds of heavy toxic gases.[5] The CWS data show a decrease in contaminated area with increasing wind speed but also show a dependence upon atmospheric stability. At the same wind speed, contaminated areas are greater when the air is stable than when it is unstable. The effect of wind speed on deposit area is greater when the air is stable.

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[5] W. M. Latimer, "Behavior of Gas Clouds", Military Problems with Aerosols and Nonpersistent Gases, Summary Technical Report of Division 10, NDRC, Vol 1, Washington, D. C., 1946, pp 260-283.

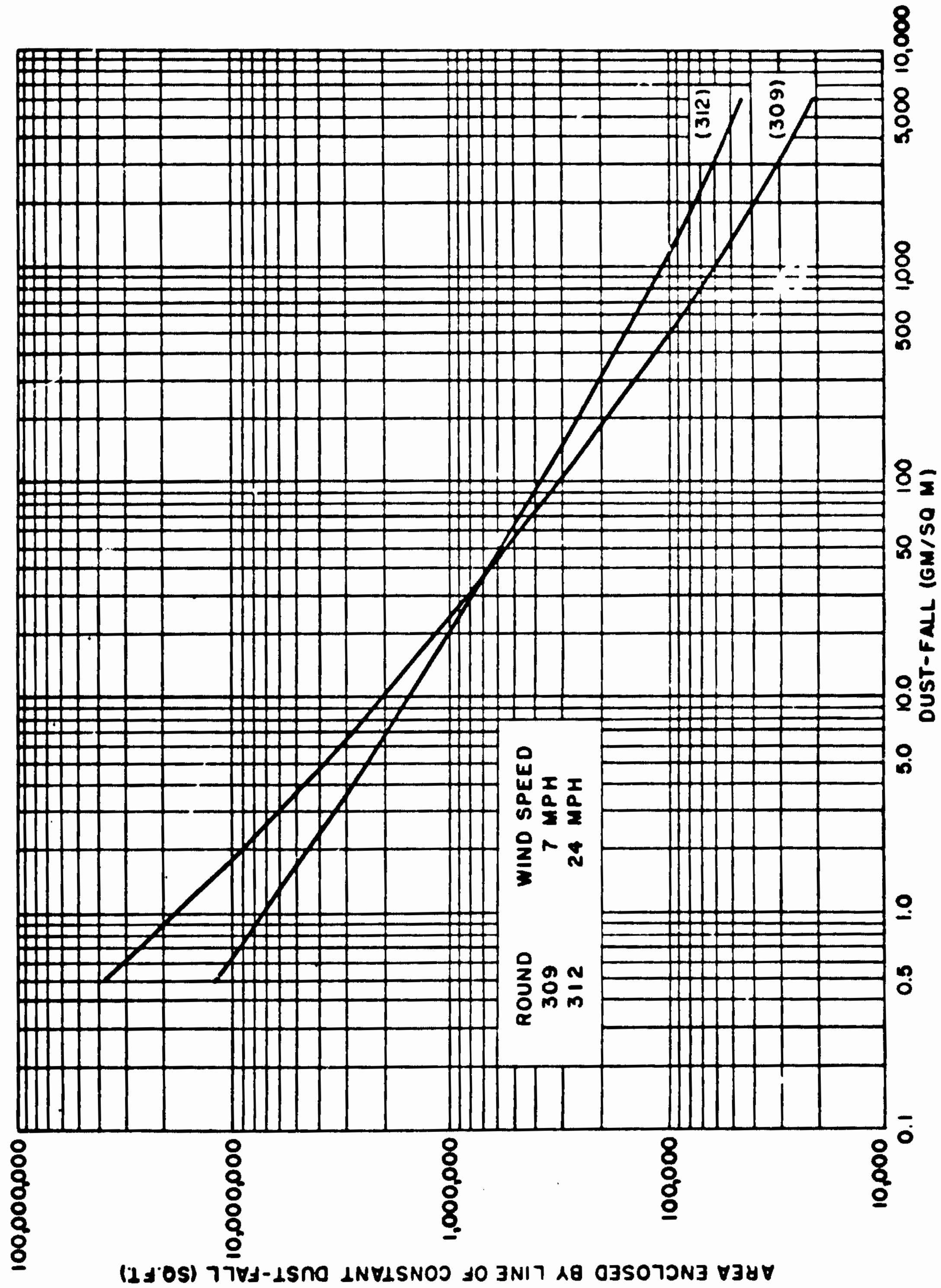


Fig. 5.2 Effect of Wind Speed on Distribution of Dust-Fall

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As the correlation of areas of dust-fall from underground explosions with a single observation of wind speed is an oversimplification, it will be helpful to examine the character of the wind and the general state of local weather for Rounds 309 and 312 in order to gain some insight into the character of atmospheric stability and turbulence when the charges were fired.

Round 309 was exploded at 1106:30 MST on 18 April 1951. The surface wind direction varied from 140° to 50° about the time of the shot but a pilot balloon ascension after the burst indicated a surface wind from 280° at 7 mph and a 1000 ft wind from 280° at 6 mph. The U. S. Weather Bureau Daily Weather Map showed a weak low pressure area in the Utah region on 18 April, with showers and thunderstorms starting in the late evening. These wind and weather conditions show a slowly varying light wind and probable thermal instability in the Dugway region.

Round 312 was fired at 1621:20 MST on 4 May 1951. The surface wind instruments were not operating but a pilot balloon ascension at 1322 MST showed a surface wind from 180° at 30* mph and a 1000 ft wind from 190° at 40 mph. After the shot no release was made, due to the high and gusty surface winds. The photographs of the shot show an altocumulus overcast at Dugway. The gustiness and pronounced wind shear in the vertical combined with the overcast sky indicate considerable mechanical turbulence with little or no thermal instability.

The fluctuations of wind velocity indicate directly the turbulent motion of the atmosphere and provide information on the nature and size of the eddies which form in the turbulent air. In general the low frequency components of the velocity fluctuations indicate large diameter eddies and the higher-frequency components represent small eddies, or those in more rapid eddy-motion.[6] The dispersal of a particulate cloud depends upon the relative size of the predominant eddies.

The wind data and probable vertical convection on the day Round 309 was fired indicate the presence of relatively large, slowly-moving eddies, which were able to disrupt the dust cloud after gravitational

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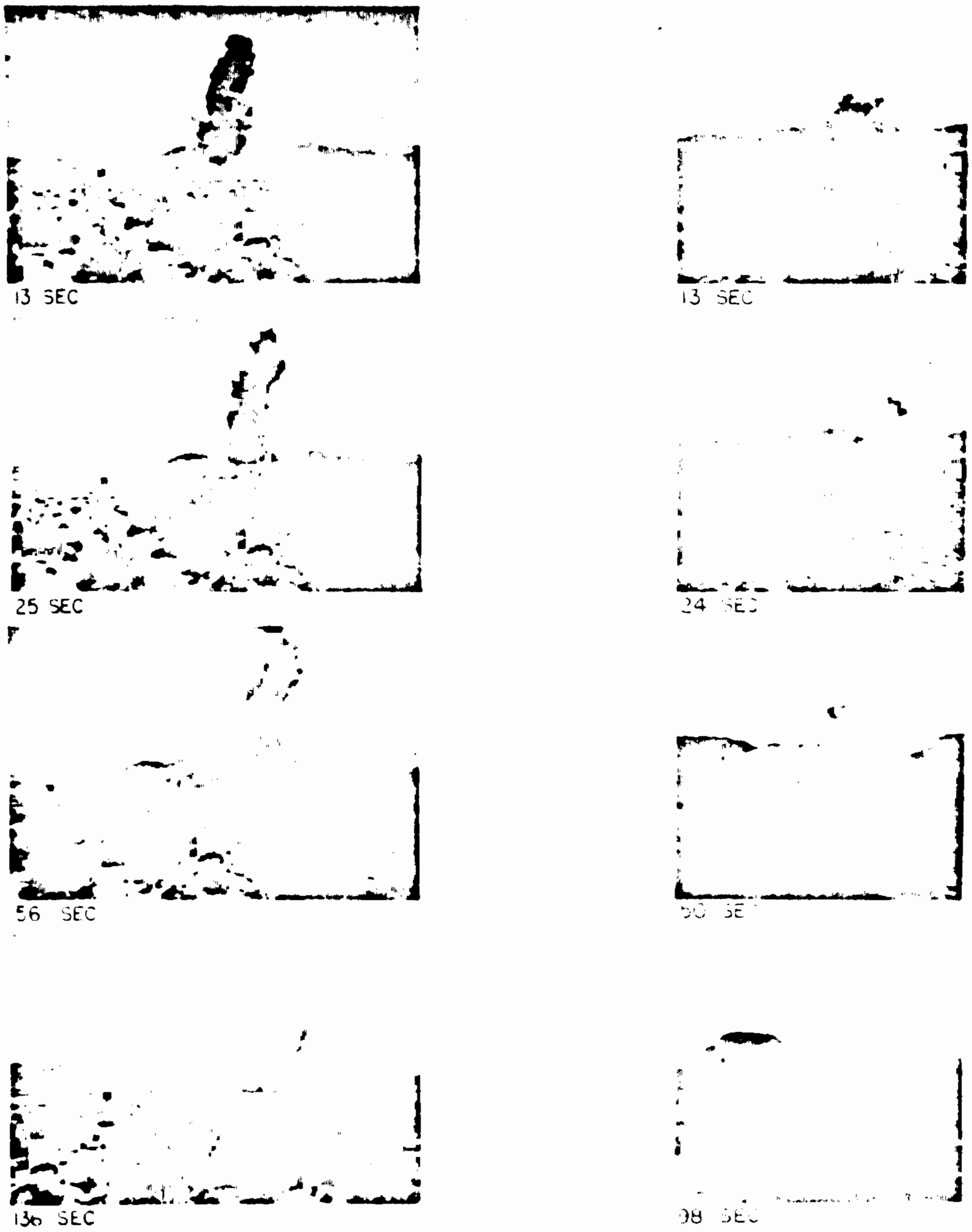
* The value of 24 mph assigned to the time of the shot was obtained by triangulation of the dust cloud movement shown by E.R.A. still photographs.

6 S. W. Grinnell, W. A. Perkins and F. X. Webster, Bimonthly Report No. 3 of Chemical Warfare Service Research and Development Program, Contract No. W-18-035-CWS-1256, Stanford Univ., Calif., May - June 1946, p 26.

flow had effectively ceased and spread it over a wide area. The path of an airborne particulate cloud is difficult to predict in this type of meteorological condition. The atmospheric eddies on 4 May were probably smaller than the Round 312 dust cloud and did not have the same effect.

The base surge and resulting dust clouds for Rounds 309 and 312 are shown in Fig. 5.3. The jet produced by Shot 309 rose to a great height and became diffuse, contributing only part of its material to the base surge. The surge cloud ultimately rose from the ground and gradually mixed with the air. The jet from Round 312 was shorter and fell rapidly, probably contributing all of its material to the base surge, which grew at an exceptionally fast rate and tended to hug the ground surface without rising appreciably. The strong wind and turbulence caused a more uniform distribution of dust than for Round 309.

Jet height and surge radius for the two rounds are shown as functions of time in Fig. 3.11.




ROUND 309
SURFACE WIND : 7 MPH

ROUND 312
SURFACE WIND = 24 MPH

CHARGE WEIGHT = 2560 LB
CHARGE DEPTH = 7.0 FT
SCALED DEPTH = 0.512 FT/LB$^{1/3}$

**Fig. 5.3 Effect of Wind Speed on Surface Phenomena**

# CHAPTER 6

## CRATER ANALYSIS

### 6.1 EFFECT OF SCALED CHARGE DEPTH ON CRATER DIMENSIONS

A study of the size of the true and apparent craters formed by underground explosions gives some insight into the mechanism of ejection of soil into the air and its subsequent fall-back. In particular, the weight of soil that enters the airborne dust cloud can be estimated fairly directly by using crater dimensions.

Crater measurements for the Dugway Tests were obtained from E.R.A. Interim Technical Reports No. 1,[1] 2,[2] and 3[3] and data on the Nevada high-explosive tests from JANGLE Report 1(9)-3, by LCDR. D. C. Campbell.[4]

To study some of the effects of charge weight and depth, the assumption can be made that the volume of the apparent crater remaining after a charge is fired indicates the approximate amount of soil that is ejected from the crater and enters the column, jet, smoke crown, and base surge. Inaccuracies are introduced by changes in soil density, and probably only a small percentage of this ejected soil remains aloft for more than a few seconds, but a comparison of the soil volumes ejected at different scaled depths gives an indication of the relative effectiveness of various charge positions for producing dust-cloud phenomena. The amount of soil falling directly back into the crater and lip can be

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[1] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 1, Dry Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Aug. 1951, pp 2-12.

[2] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 2, Dry Sand, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Oct. 1951, pp 2-18.

[3] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 3, Wet Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Nov. 1951, pp 2-8.

[4] D. C. Campbell, LCDR, USN, Tests and Observations on Craters and Base Surges, JANGLE Report 1(9)-3, 1 Nov. 1951.

estimated by obtaining the difference between the real and apparent crater volumes and adding the lip volume, but it is assumed that this direct fall-back has a negligible effect on the surface flow phenomena.

Figure 6.1 is a plot of apparent crater volume vs scaled depth and shows a maximum volume of about $\lambda_c = 1.0$ ft/lb$^{1/3}$ for 320 lb charges fired in dry sand. The remaining data is consistent in showing a similar trend for greater charge weights but does not cover a sufficient range of depth to indicate a maximum value.

A second way of assessing the effectiveness of a charge in producing an airborne dust cloud is to examine the ratio of the depth of the apparent crater to the charge depth. As shown in Fig. 6.2, the apparent crater depth is considerably greater than charge depth for shallow shots, but becomes equal to charge depth at scaled depths somewhat greater than 1.0 ft/lb$^{1/3}$ and decreases to considerably less than charge depth for deeper charges, particularly in dry clay. Physically, this indicates that with deeper charges, much of the soil in the column and jet drops back into the relatively deep true crater and remains there.

It is of interest to compare the ratios of the diameter of the true crater to maximum column diameter, as the true crater may indicate the size of the rising jet. Fig. 6.3 shows that the column is about twice the crater size for charges fired between scaled depths of 0.135 and 1.02 ft/lb$^{1/3}$, but approaches crater diameter when charges are fired at deeper positions. When the column expands only slightly beyond the limits of the crater, much of the falling soil will drop down into the crater and remain there. For scaled depths greater than $\lambda_c = 3.07$ ft/lb$^{1/3}$, column diameter probably becomes equal to crater diameter, to the maximum depth at which craters will form (about $\lambda_c = 5.0$ ft/lb$^{1/3}$).[5]

Probably the optimum condition for base surge formation is obtained when the rising column attains a diameter twice the crater diameter, at about $\lambda_c = 1.0$ ft/lb$^{1/3}$. When the charge is very shallow, the relatively wide column formed has a bulk density too low to set up the pronounced density current needed for the formation of a large clearly-defined base surge.

The crater measurements presented here are consistent with the measured areas of dust deposit in indicating that a maximum volume of airborne soil is produced by a charge fired at a scaled depth of about

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[5] C. W. Lampson, "Underground Explosions", Appendix B, The Effects of Atomic Weapons, U. S. Atomic Energy Commission, Washington, D. C., Sept. 1950, p 421.

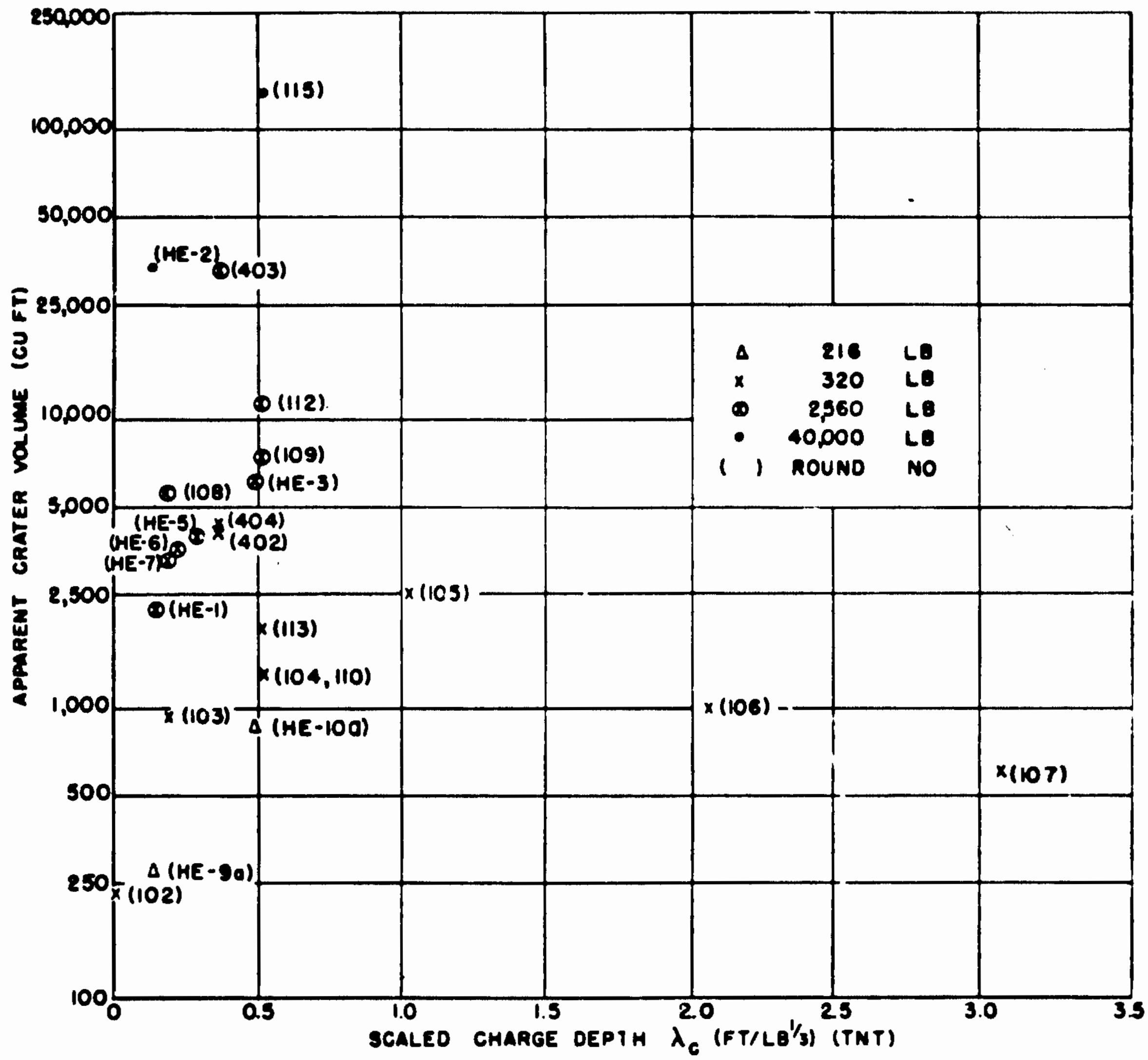


Fig. 6.1 Apparent Crater Volume vs Scaled Charge Depth

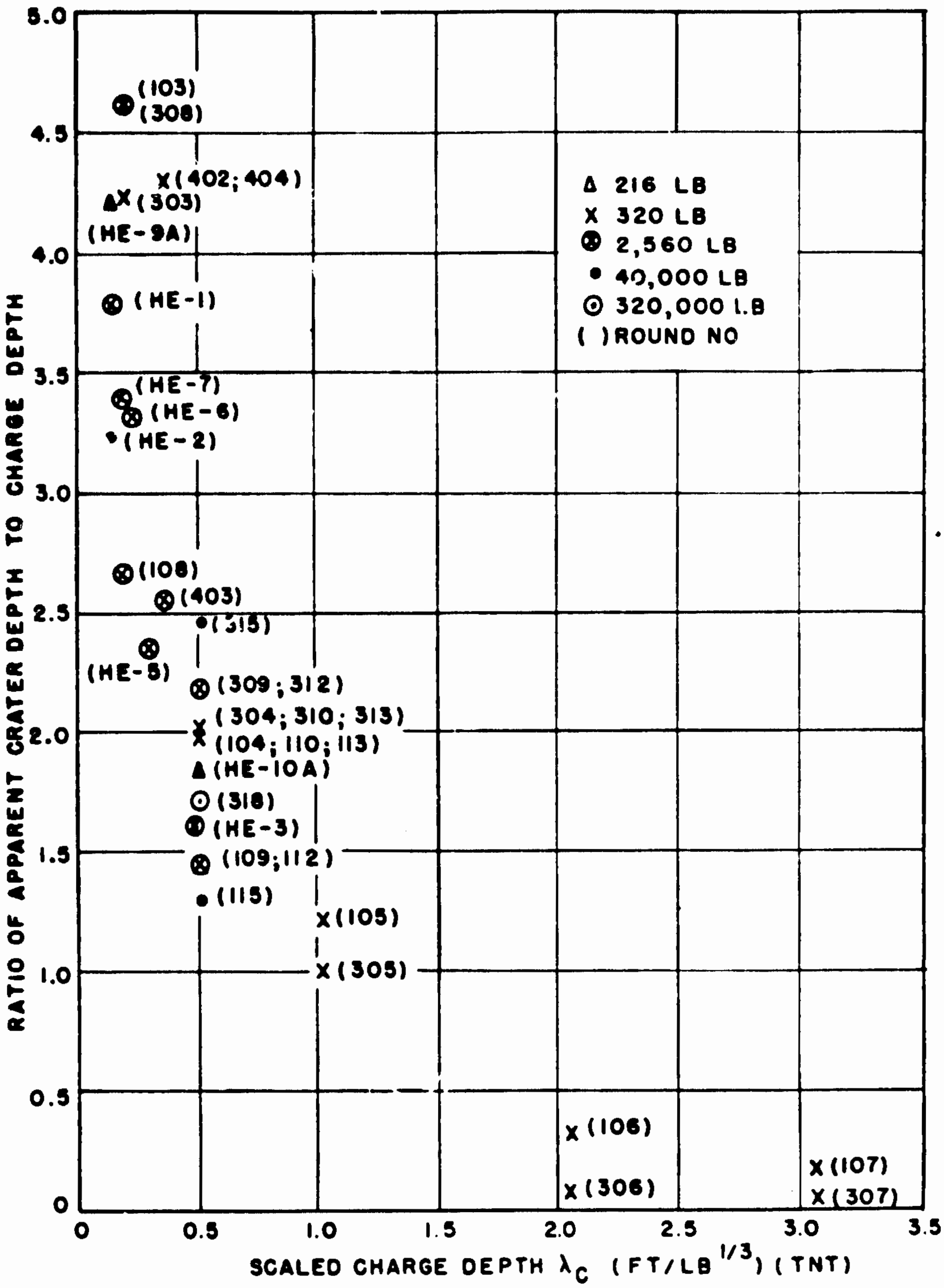


Fig. 6.2 Ratio of Apparent Crater Depth to Charge Depth vs Scaled Charge Depth

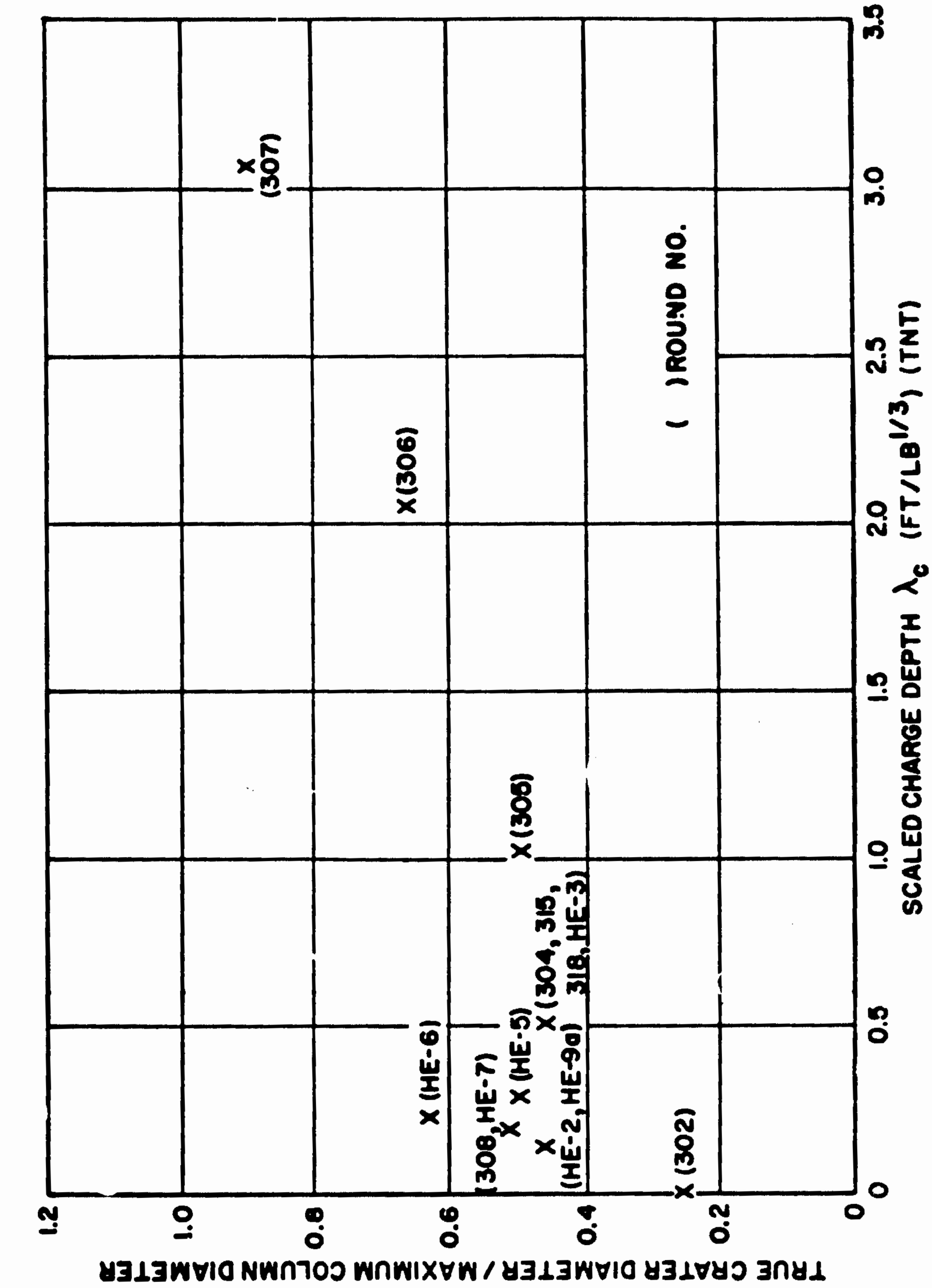


Fig. 6.3 Ratio of True Crater Diameter to Maximum Column Diameter vs Scaled Charge Depth

$\lambda_c = 1.0\ \text{ft/lb}^{1/3}$.

In these studies, the largest craters were produced in wet clay, indicating that crater size alone is not a good criterion of the effectiveness of the charge in producing a base surge. Crater size will aid in the estimation of the amount of soil raised into the air, but the behavior of the ejected soil depends upon its physical characteristics, such as moisture content, particle size and cohesiveness.

# CHAPTER 7

## SOIL EFFECTS

### 7.1 SOIL CHARACTERISTICS FAVORABLE FOR BASE SURGE FORMATION

The size and rate of growth of the base surge produced by an underground explosion is obviously dependent upon the nature of the soil. The amount of data available is not adequate for a quantitative study of the soil effect, but the records of the Dugway series in three soil types indicate that well-developed surges are formed in dry sand, dry clay, and wet clay, with the largest surge clouds resulting from the dry sand tests and the smallest from the wet clay. The surge clouds produced in the Nevada high explosive tests were similar to those in the Dugway dry clay rounds, though the soil appeared to be a mixture of limestone, sand, and clay.[1]

It may be significant that the seismic velocities ranged from 750 to 2000 fps at the dry sand site,[2] from 2500 to 3500 fps at the dry clay site,[3] and from 5000 to 6000 fps in the wet clay.[4] The seismic velocity at the Nevada test site was 3000 fps.[5]

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[1] R. D. Cadle and A. G. Wilder, Composition of Clouds Formed by TNT Explosions, (HE Tests-Operation JANGLE), Technical Report No. 3, Stanford Research Institute, Stanford, Calif., ONR Project NR 350-023, SRI Project 412-317, Oct. 1951, p 5.

[2] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 2, Dry Sand, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Oct. 1951, p 2-19.

[3] Underground Explosion Tests, Program "A", Tests in Soils, Protective Construction Branch, Engineering Division, Office, Chief of Engineers, Nov. 1950, p 2.

[4] Instrumentation for Underground Explosion Test Program, Interim Technical Report No. 3, Wet Clay, Engineering Research Associates, Inc., Contract No. DA-04-167-eng-298, 1 Nov. 1951, pp 2-49 to 2-51.

[5] Interim Report - HE Tests - Operation JANGLE, Project 1(9), Stanford Research Institute, Stanford, Calif., Oct. 1951, p 3.

It appears, therefore, that the size of the base surge formed by an underground explosion is related inversely to the velocity of propagation of seismic waves in the soil. This seems reasonable, as heavy plastic wet clays are good transmitters of seismic waves while light loamy soils are very poor in this respect.[6] The highly cohesive clays do not separate easily into the fine particles needed to establish a downward density current and radial base surge, while the powdery low-cohesive soils are favorable for the formation of such a density flow and the development of a light particulate cloud which will propagate for a long distance. In general, wet soils would be less suited to base surge formation than dry soils.

Thus, the available data indicate that a single soil characteristic - the seismic velocity - might be used as an indicator of the probable success of a soil type as a base surge producer. If this point of view is correct, a soil type such as dry loess would be one of the most favorable for the production of a large, long-persisting base surge.

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[6] C. W. Lampson, "Underground Explosions", Appendix B, The Effects of Atomic Weapons, U. S. Atomic Energy Commission, Washington, D. C., Sept. 1950, pp 410-416.

# CHAPTER 8

## EFFECT OF CHARGE SIZE

### 8.1 GENERAL

The data presented in this report were obtained from records of TNT explosions. Results were fairly consistent for similar soil types and scaling was generally satisfactory for charges weighing from 320 to 320,000 lb at scaled depths ranging from 0.185 to 2.05 $ft/lb^{1/3}$. However, the simple scaling methods used were not adequate for very shallow and very deep charges and possibly would not apply outside the range of weights used. In addition, the possibility exists that explosives other than TNT might produce somewhat different surface phenomena, due to differences in explosion products, energy per unit volume, heat of detonation, or other factors.

The effects of charge size and shape might become important for shallow explosions, when part or all of the charge is exposed to the air at detonation. The scaled depth of 0.135 $ft/lb^{1/3}$ is probably transitional for spherical TNT charges, because the top of the charge is tangent to the surface of the ground at this position. The characteristics of the surface phenomena change markedly in this shallow zone, and the base surge becomes very tenuous and difficult to detect, though a true, but weak, density flow exists at $\lambda_c = 0.135\ ft/lb^{1/3}$.

The size and rate of growth of a base surge depend upon the volume of earth ejected from the ground and the size and concentration of the soil particles in the earth column. As shown in Fig. 8.1, the volume of the true crater decreases rapidly with decreasing charge depth in the shallow range, indicating that considerably less soil is thrown into the air by shallow charges, and the relatively wide columns at $\lambda_c$ = zero indicate that the soil particles are widely separated.

The lack of a soil covering above the charge probably reduces the efficiency of the explosion as a producer of a base surge, though it should not be inferred that only the soil above the charge enters the base surge. Visual study of the films of underground explosions shows that the ground surrounding a charge is lifted into an earth column which drops and flows outward to form the base surge. The earth directly above the charge is probably carried upward by the rising jet.

The effect of the thickness of the earth covering (overburden) above a charge might be determined by firing explosives with a greater energy per unit volume than TNT at the same scaled depths as the equivalent TNT charges. Another possible experimental approach would be

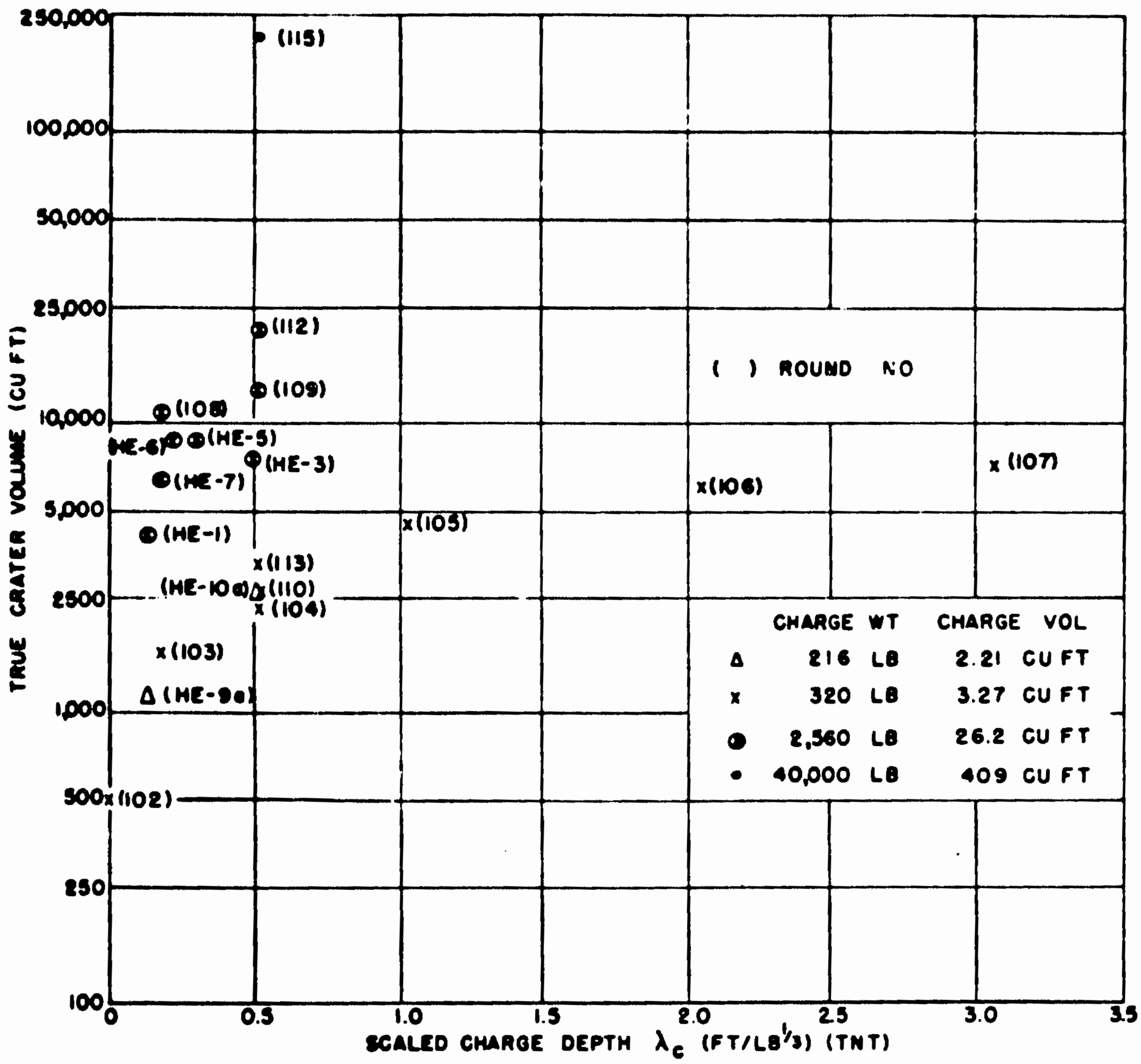


Fig. 8.1 True Crater Volume vs Scaled Charge Depth

the use of a series of TNT charges of different shapes but the same weight, with the center of gravity at the same depth.

If an explosive with the equivalent energy of a charge of TNT, but smaller in size, produces a crater equal in size to the TNT crater, it might be assumed that the additional volume of soil displaced would favor the formation of a larger surge. However, within the range of energy density of conventional high explosives, differences in charge volume are insignificant when compared to the total volume of soil ejected from the crater.

## 8.2 COMPARISON OF TNT AND PENTOLITE

A test of the effect of charge volume on the base surge was conducted as part of the HE program at Nevada.[1] The experiment consisted of simultaneous detonations of 216 lb of TNT and 177 lb of Pentolite, with equivalent energies, fired at scaled depths of 0.181, 0.139, and 0.500 ft/lb$^{1/3}$. (See Table 1.2.)

Round HE-8 ($\lambda_c$ = 0.181) was not satisfactory, due to inadequate priming of the TNT charge and an anomalous behavior of the Pentolite jet, which rose to an exceptionally great height.

Rounds HE-9 ($\lambda_c$ = 0.139) and HE-10 ($\lambda_c$ = 0.500) produced clearly defined base surges. The surge radii and heights are given in Figs. 8.2 and 8.3, and overall heights are shown in Fig. 8.4, as functions of time. Unsmoothed surge data is shown for both shots, and two camera records are given for HE-9, to illustrate the degree of scatter and lack of consistent trends. There appears to be no significant difference between the radial growth and extent of the surge clouds produced by the two explosives, but considerable difference appears in the growth of the jet. The pentolite jets rose to greater heights in both cases and were whitish in appearance, while the jets formed by TNT were black. Following Round HE-9, both jets remained airborne and drifted with the wind but for HE-10 the jet produced by TNT fell rapidly while part of the Pentolite jet remained aloft. Some of these effects are illustrated in Fig. 8.5.

This test showed how above-ground activity might vary with different explosives, but did not show any significant effect of charge volume on the size of the base surge. The earth cover was 1-1/8 inches over

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[1] D. C. Campbell, LCDR, USN, Tests and Observations on Craters and Base Surges, JANGLE Report 1(9)-3, 1 Nov. 1951.

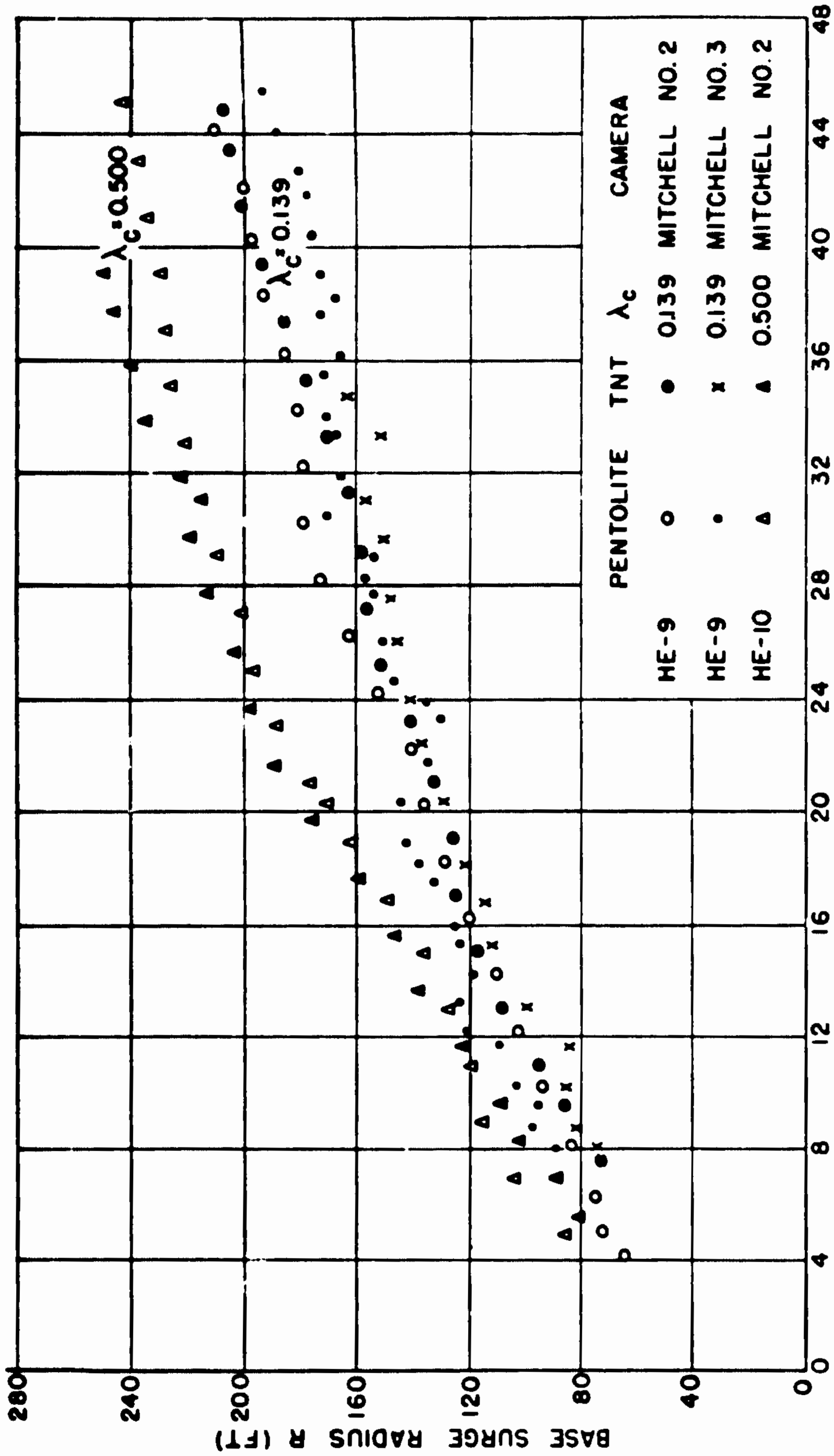


Fig. 8.2 Base Surge Radius vs Time - TNT and Pentolite Comparison

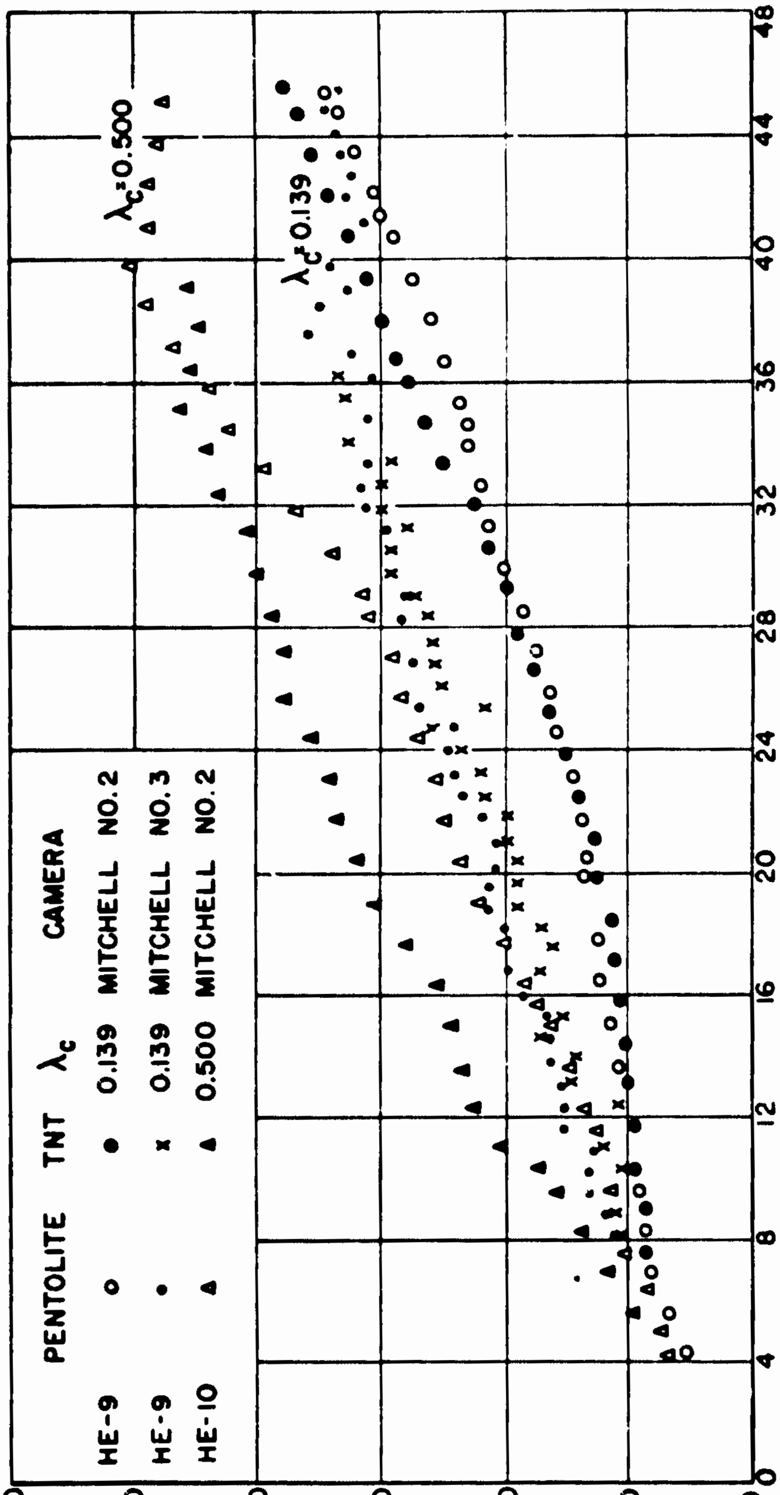


Fig. 8.3 Base Surge Height vs Time - TNT and Pentolite Comparison

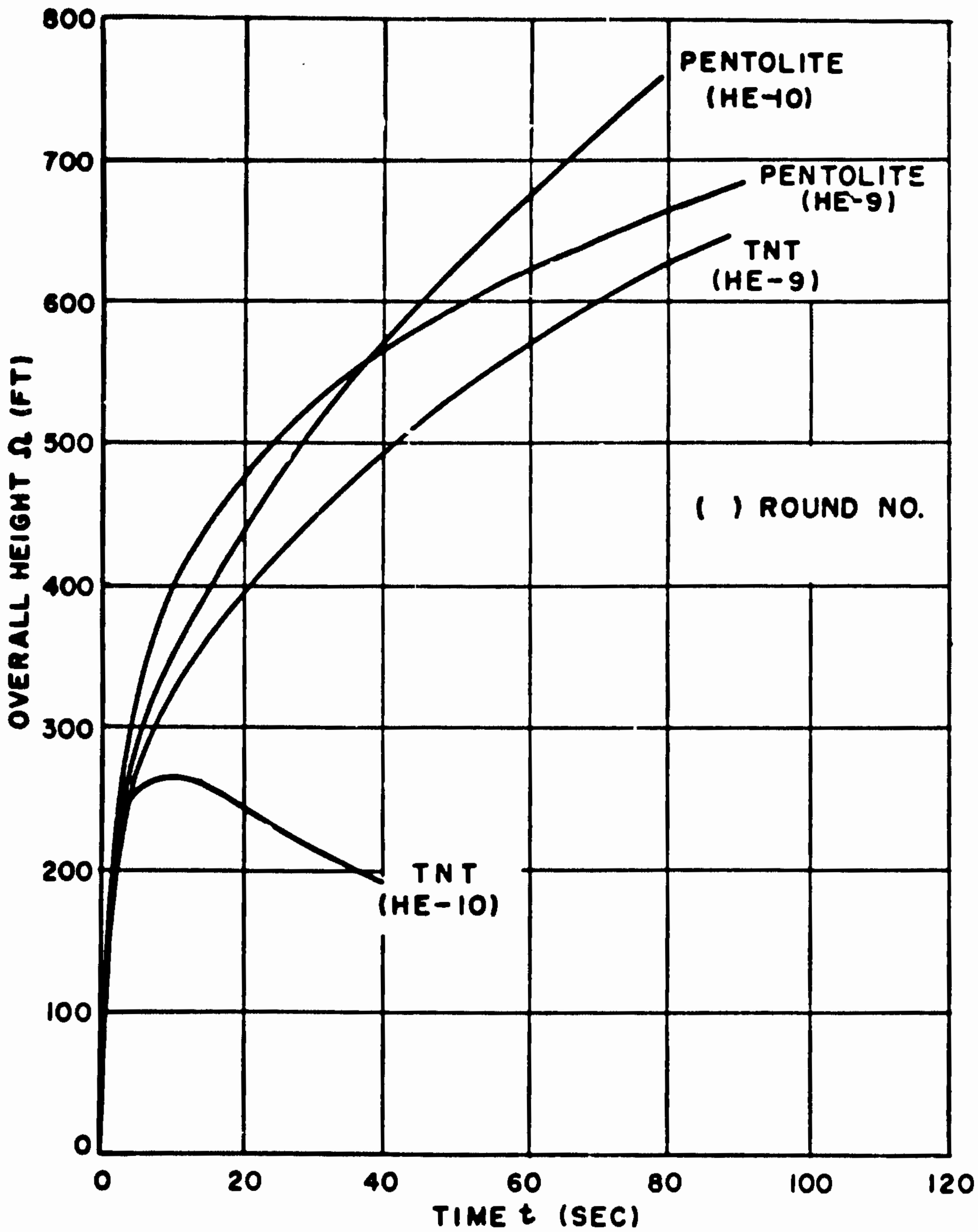


Fig. 8.4 Overall Height vs Time - TNT and Pentolite Comparison

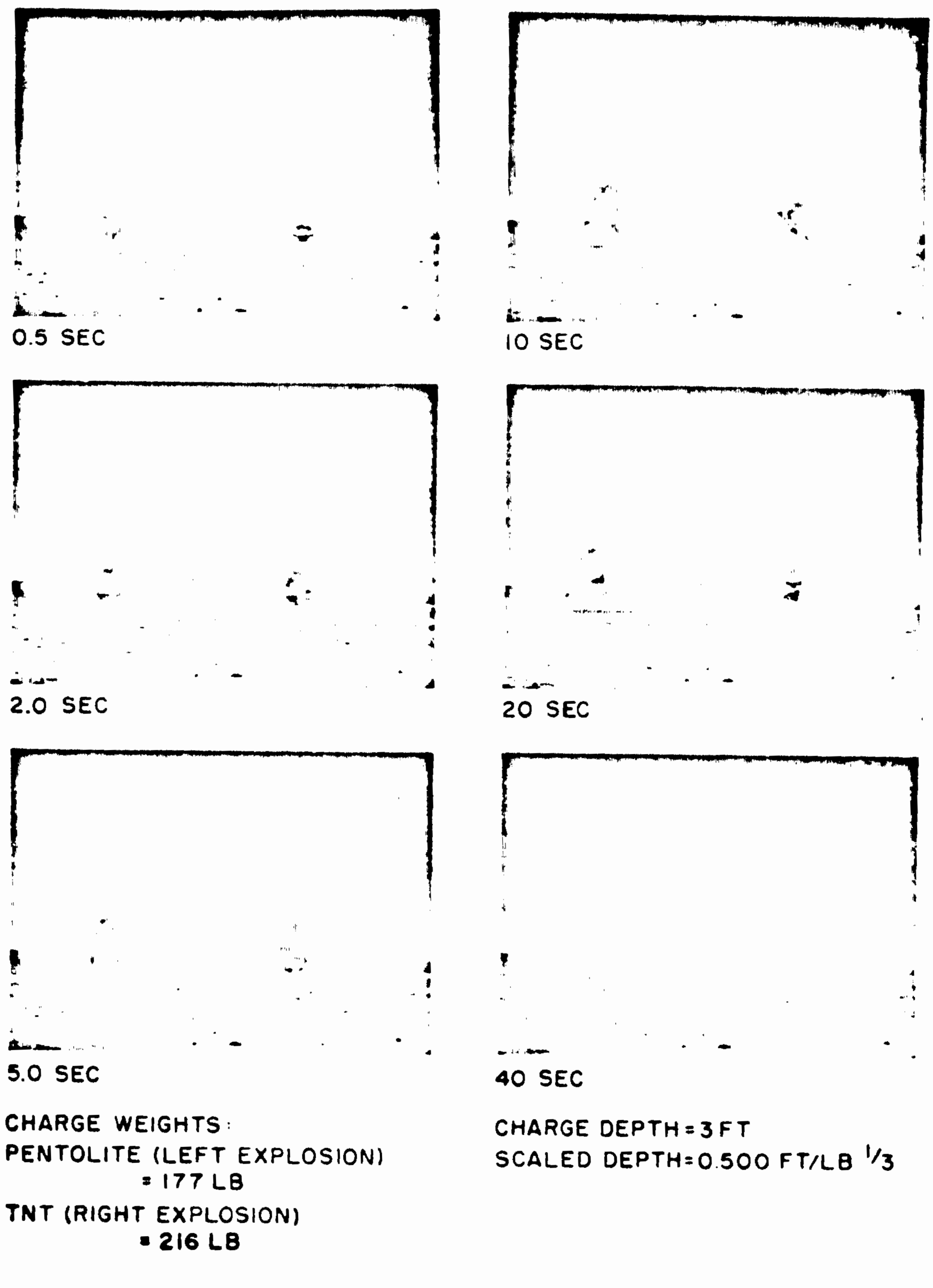


Fig. 8.5 Surface Phenomena Produced by TNT and Pentolite - Round HE-10

the Pentolite charge and zero over the TNT charge for Round HE-9 but surge growth was essentially the same. For this round the volume of the true crater formed by Pentolite was 1310 cu ft and the TNT true crater volume was 1120 cu ft. The difference between charge volumes was 0.52 cu ft.

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